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Assessment and Rehabilitation Strategies/Guidelines to Maximize the Service Life of Concrete Structures

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ASSESSMENT AND REHABILITATION STRATEGIES / GUIDELINES TO MAXIMIZE THE SERVICE LIFE OF CONCRETE STRUCTURES

FINAL REPORT

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16. Abstract

This report presents a spreadsheet tool for evaluating life-cycle maintenance strategies for existing concrete bridge decks that have deteriorated as a result of chloride-induced corrosion. The spreadsheet tool construct a performance curve for existing bridge decks, computse the estimated service life of common treatments for bridge decks such as patching, concrete or asphaltic overlays as well as that of a new deck with epoxy coated bars, conducts a life-cycle cost analysis for common maintenance scenarios, and determines the optimal maximum (tolerable) condition index that minimizes total life-cycle maintenance cost. The life-cycle cost analysis is probabilistic. Also, this report provides a library of alternative life-cycle treatment scenarios and offers distribution functions for estimated unit costs. Both agency and user costs are considered.

A case study analysis was conducted using the tool. Findings and conclusions suggest that the least cost maintenance scenario may depend on the choice of discount rate. The most significant findings are that total life-cycle cost (user cost plus agency cost) is a function of the maximum tolerable condition S_m. and that the function can be optimized to find the value of S_m that minimizes the total life-cycle cost.

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EXECUTIVE SUMMARY

Project summary

This research provides a spreadsheet tool for evaluating life-cycle maintenance strategies for existing concrete bridge decks that have deteriorated as a result of chloride-induced corrosion. The spreadsheet tool predicts and models deterioration, and estimates the life-cycle cost of alternative treatment scenarios. The life-cycle cost analysis is probabilistic. Also, this report provides a library of alternative life-cycle treatment scenarios and offers distribution functions for estimated unit costs. Both agency and user costs are considered.

Background

According to the state bridge inventory, Wisconsin has over 9,700 concrete bridge decks. District and county engineers are frequently required to choose between alternative maintenance treatments for dealing with decks that have deteriorated as a result of chloride-induced corrosion. Of the existing concrete bridge decks, 1,580 have been given a concrete overlay, 713 have been given an asphaltic overlay and, 378 have been given an AC overlay with a membrane. The number of bare decks is 7,062 with an average age of 20 years. District and county engineers have no tools to assist in the decision making process at the project level. The purpose of the research is to provide a decision support tool for estimating cost and service life of maintenance strategies for concrete bridge decks at the project level.

The Department of Civil and Environmental Engineering at University of Wisconsin-Madison through the Wisconsin Highway Research Program conducted the project. The Research Team included Teresa M. Adams (Professor and Principal Investigator), Jose Pincheira (Associate Professor), Ying-Hua Huang (Graduate Student), and Beth Miller (Graduate Student). The Project Committee, chaired by Stanley W. Woods (WisDOT Central Office), included Edward Fitzgerald (District 5), Mike Pheifer, Thomas, Strock (FHWA), and Frederick Wisner (WisDOT Central Office).

Process

The spreadsheet tool adapts and implements a mechanistic deterioration model and a methodology for estimating service life of concrete with chloride-induced corrosion. The deterioration models in the spreadsheet tool were calibrated for Wisconsin bridge data. The data used in this study included the percentage of distressed area (spalled or delaminated) in concrete decks. These data were obtained from the element-level inspections reported by bridge engineers. In addition, this study used chloride content data obtained for the decks of bridges B-41-43 (District 5) and B-35-10 (District 7). Frederick Wisner at WisDOT central office supplied these reports. For bridge B-35-10, Francis W. Bennett (District 7) supplied additional data from deck sounding inspection reports.

The tool was developed to make use of element-level inspection data being collected by the districts. The condition index curve was calibrated to condition state valued assigned by bridge inspectors. Consequently, project level recommendations from the spreadsheet tool are consistent with network level recommendations from the State's bridge management system (BMS).

The project was completed in 24 months. Initial research activities involved the identification and evaluation of nondestructive testing (NDT) methods for assessing the condition of concrete bridge elements. This was accomplished through a literature review and a survey questionnaire sent to bridge maintenance engineers at all eight Districts in Wisconsin. The Research Team developed charts that correlate distress in concrete bridge elements with NDT methods for measuring the distress. A wide range of NDT methods exist and some are being used by Wisconsin districts, particularly for detecting delamination in bridge decks.

Based upon initial research findings, the Project Committee recommended that the research plan concentrate on decision-making for treating corrosion and delamination of bridge decks. Subsequently, the Research Team reviewed the published literature on mechanistic models of deck deterioration and maintenance actions for concrete decks. With approval of the Project Committee, an existing approach by Babaei et al. was adapted and coded as an Excel spreadsheet application. The Research Team met with bridge maintenance engineers from

Districts 1 (Matthew Murphy) and 5 (Edward Fitzgerald and Peter A. Luebke) for the purpose of obtaining estimates of unit costs, productivity, and service life of various maintenance strategies. The spreadsheet tool incorporates the cost and productivity estimates as default values for life-cycle cost analysis. The service life estimates were used to calibrate the software tool.

Finally, this study includes a sensitivity analysis of the model parameters. The analysis qualifies the influence of agency cost, treatment timing, maximum tolerable condition index, estimated service life, and treatment effectiveness on the total life-cycle cost of maintenance. The purposes of the sensitivity analysis were to obtain general guidelines for using the tool and recommendations for selecting maintenance strategies and treatment timing.

Findings and Conclusions

The project-level tool developed in this investigation allows bridge maintenance engineers to:

a) construct a performance curve for existing bridge decks, either repaired or not repaired previously,

b) compute the estimated service life of common treatments for bridge decks such as patching, concrete or asphaltic overlays as well as that of a new deck with epoxy coated bars,

c) conduct a life-cycle cost analysis for common maintenance scenarios, and

d) determine the optimal maximum (tolerable) condition index that minimizes total life-cycle maintenance cost.

A case study analysis was conducted using the tool. Findings and conclusions suggest that for concrete deck maintenance, the choice of discount rate can significantly affect the total life-cycle cost of a given maintenance scenario such that least cost maintenance scenario may depend on the choice of discount rate. The most significant findings are that total life-cycle cost (user cost plus agency cost) is a function of the maximum tolerable condition S_m. and that for the range of S_m considered, the relationship between total life-cycle cost and S_m is convex. This means the function can be optimized to find the value of S_m that minimizes the total life-cycle cost. The test case shows that the minimum total life-cycle cost may not be achieved at the tolerable index currently used in Wisconsin (S_m =23). The spreadsheet tool can be used to find the value of tolerable index that minimizes life-cycle cost.

Recommendations for Further Action

First, the Research Team recommends that the percentages of spalled and delaminated areas be collected and recorded as separate data items when bridges are inspected. Mechanistic deterioration models treat delamination and spalling as distinct phases in the deterioration process. The individual percentages of spalled and delaminated areas can have a significant influence on the calculated condition index of the deck.

Second, the Research Team recommends that a study be conducted to cross exam and corroborate percentage of delaminated area that are measure from chain drag, Infrared Thermography (IRT), and Ground Penetration Radar (GPR) methods.

Third, the Research Team recommends that WisDOT collect chloride content measurements for concrete bridge decks or that WisDOT prepare a table of default values for chloride content as a function of concrete age, roadway functional class, and salt rate for winter maintenance. Chloride content is an essential parameter for modeling the deterioration and estimating the service life of existing bridge decks with and without treatment. Samples of the chloride content at the bar level are not collected in routine inspections and thus are unavailable for the majority of existing bridge decks.

Fourth, the Research Team recommends that WisDOT collect the model parameters (cost, service life, productivity) necessary to include chloride extraction, corrosion inhibitors, and cathodic protection as possible maintenance scenarios in the library of strategies known to the software application. The spreadsheet tool can be useful for evaluating the economics of these strategies as compared to more traditional strategies such as concrete overlay.

Finally, the Research Team recommends that WisDOT identify an “implementation champion” at the Central Office who will work with the Districts to further test and refine the software parameters and user interface so that the tool is integrated into the bridge management business function.

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CHAPTER 1. INTRODUCTION

1.1 Problem Statement

More than one half million bridge structures exist in the national bridge inventory and nearly half of them are 30 to 50 years old (1). A major concern of state and local transportation agencies is the deterioration of concrete bridge decks over 15 years old (2). The leading cause of deck deterioration is chloride-induced corrosion of the black steel reinforcing bars. Epoxy coated bars are now routinely used in new decks when chlorides are a concern. This practice is expected to lengthen the service life of concrete decks by delaying the effects of corrosion. The effects of corrosion are delamination, spalling, and loss of reinforcing bar area. To deal with this problem, bridge maintenance engineers need better tools to analyze alternative treatment strategies and to aid decision-making at the project- and network-levels.

1.2 Objectives

This research focuses on deterioration and rehabilitation of concrete decks. The main purpose of this research was to develop a project-level decision support tool that can assist district engineers with predictions of remaining life, and the assessment and selection of maintenance actions for concrete bridge decks deteriorated due to chloride-induced corrosion of the steel reinforcement.

Background

1.3.1 Nondestructive Testing (NDT)

The Research Team reviewed nondestructive testing methods in two ways: questionnaire and literature review. Through a questionnaire sent to all districts, the Research Team obtained information about the current and potential uses of NDT methods by the districts. The personnel contacted in each district are listed in Table 1.

Six NDT methods listed in Table 2 are used to inspect concrete bridges. Other methods used to measure deformation (strain gages, laser displacement, and electronic tilt meters) or applied to steel elements are not listed here. Most respondents think NDT has potential for standard use in bridge inspection.

Table 1. Bridge maintenance engineers contacted in districts

District	Bridge Maintenance Engineer	Phone Number
1	Matthew Murphey	(608) 246-3250
2	Bunmi Olapo	(262) 548-6470
3	Howard Krook	(920) 492-5647
4	Thomas J. Hardinger	(715) 421-8323
5	Peter A. Luebke	(608) 785-9041
6	D. Patrick Kern	(715) 836-3918
7	Francis Bennett	(715) 365-5756
8	Allan Bjorklund	(715) 392-7951

Table 2. NDT methods in use by districts

Method in use	District Number							
	1	2	3*	4	5*	6	7	8
Impact Echo	X							
Acoustic Emission	X							
Chain Drag	X			X	X	X	X	X
Hammer Sounding	X				X			X
(Infrared) Thermography		X		X		X		
Ground Penetrating Radar				X		X		

*NDT is done by contract through the Central Office.

Based upon a literature review, the Research Team completed a narrative summary for each of the 14 Nondestructive Testing (NDT) methods for concrete elements listed in Table 3. In each summary report, the purpose, basic principle, application, test results and data interpretation, case studies, reliability of procedure, cost, advantages and limitations, applicability to bridges, and references for each method are described.

The Research Team evaluated the potential of each NDT method for detecting distress in concrete bridge elements. The results are summarized in Table 4. The table lists the element most frequently occurring concrete elements in the WisDOT bridge inventory according to the “State 00” dataset. The white regions indicate the distresses considered in current element-level inspections (e.g. as listed in the WisDOT bridge inspection pocket manual), while the shaded areas show those that are not considered.

Table 3. NDT methods for the assessment of the in-service condition of concrete

Method	**Purpose**
Sounding with hammer	Detect delaminated areas (spalls)
Sounding with chain drag	Detect delaminated areas
Impact Echo (IE)	Detect subsurface flaws (cracks or voids)
Ultrasonic Pulse Velocity (UPV)	Detect subsurface flaws (cracks or voids)
Covermeter	Measure the depth of reinforcing steel from the surface
Half cell Potential	Determine the corrosion activity of the reinforcing steel
Resistivity	Measure the rate of corrosion
Polarization Resistance	Measure the rate at which corrosion is occurring at the time the test is performed
Infrared Thermography	Detect delaminations in overlaid or exposed concrete decks
Ground Pentrating Radar (GPR)	Determine concrete thickness, locating voids and reinforcing bars, and identifying deterioration
Radiography	Provide a radiation-based photography of the internal flaws of concrete members
Endoscopes	Provide a detailed view of the distress in local areas that are inaccessible
Dye Penetrants	Provide visual evidence of cracks, porosity, seams, and other surface discontinuities
Acoustic Emission	Detect subsurface defects as they occur and propagate through the member

Table 4. Nondestructive test methods for detecting distress in concrete bridge elements

<table>
<tr><th rowspan="2">Pontis Element Number</th><th rowspan="2">Element Description</th><th colspan="11">Distress</th></tr>
<tr><th>Cracks</th><th>Spalls</th><th>Scaling</th><th>Delaminations</th><th>Potholes</th><th>Wear Outs</th><th>Exposed Reinforcement</th><th>Deterioration of prestressed system</th><th>Corrosion of Reinforcement</th><th>Loss of Concrete Section</th><th>Voids and honeycombs</th></tr>
<tr><td>12</td><td>Concrete Deck No Overlay</td><td rowspan="7">Visual
Impact Echo
Dye Penetrant</td><td rowspan="11">Visual</td><td rowspan="7">Visual
Ground Penetrating Radar</td><td rowspan="5">Visual
Impact Echo
Infrared Thermography
Sounding with Hammer
Sounding with Chain Drag
Ground Penetrating Radar</td><td rowspan="7">Visual</td><td rowspan="7">Visual</td><td rowspan="7">Visual</td><td rowspan="7">NA</td><td rowspan="7">Visual
Half Cell Potential
Resistivity
Polarization Resistance</td><td rowspan="8">Visual</td><td rowspan="7">Visual
Impact Echo
Infrared Thermography
Ground Penetrating Radar</td></tr>
<tr><td>22</td><td>Concrete Deck w/ Concrete Overlay</td></tr>
<tr><td>26</td><td>Concrete Deck w/ Coated Bars</td></tr>
<tr><td>48</td><td>Concrete Slab w/ Concrete Overlay</td></tr>
<tr><td>52</td><td>Concrete Slab w/ Coated Bars</td></tr>
<tr><td>13</td><td>Concrete Deck w/ AC Overlay</td><td rowspan="2">Visual
Impact Echo
Infrared Thermography
Ground Penetrating Radar</td></tr>
<tr><td>14</td><td>Concrete Deck w/ AC Overlay & Membrane</td></tr>
<tr><td>109</td><td>P/S Concrete Open Girder</td><td rowspan="3">Visual
Ultrasonic Pulse Velocity
Impact Echo
Dye penetrant</td><td rowspan="2">Visual</td><td rowspan="4">Visual
Impact Echo
Sounding with Hammer</td><td rowspan="4">NA</td><td rowspan="4">NA</td><td rowspan="4">Visual</td><td>Visual</td><td rowspan="4">Visual
Half Cell Potential
Resistivity
Polarization Resistance</td><td rowspan="3">Visual
Ultrasonic Pulse Velocity
Impact Echo</td></tr>
<tr><td>205</td><td>Reinforced Concrete Column of Shaft</td><td rowspan="3">NA</td><td rowspan="3">Visual</td></tr>
<tr><td>331</td><td>Concrete Bridge Railing</td><td>Visual</td></tr>
<tr><td>215</td><td>Reinforced Concrete Abutment</td><td>Visual
Impact Echo
Dye penetrant</td><td>Visual</td><td>Visual
Impact Echo</td></tr>
</table>

NA: Distress is not applicable to the element

Element level inspection does not consider the distress for determining condition state

1.3.2 Deterioration Models for Concrete Bridge Decks

In 1993, Purvis and Babaei (3) described a procedure for making preservation maintenance decisions for concrete bridges subject to chloride-induced corrosion. The procedure is a project-level tool based upon a mechanistic model of concrete deterioration due to corrosion. A similar approach for predicting the service life of corrosion-induced concrete was developed by Cady and Weyers (2). In 1996, Babaei et al. (4) published a handbook that describes and extends the earlier work of Purvis and Babaei. In the procedure, concrete condition is determined from the age of the concrete, percent of area that is spalled and delaminated, and measurements of the chloride content at the concrete surface and bar level. Based on this information, a performance curve, i.e., a relationship between the condition and the age of the concrete deck can be computed.

The methodology also allows an estimate of the service life of various possible treatments for the deck, including deck replacement. The service life of a treatment (maintenance action) is a function of corrosion rate after the action is taken. Some actions may stop or slow the rate of corrosion while others do not. The service life of an action is also a function of treatment timing. The service life of the treated concrete may increase by performing a maintenance action earlier, or may decrease by performing it later.

To evaluate the long-term economic efficiency of competing alternative maintenance options, the handbook by Purvis and Babaei uses a life-cycle cost analysis (LCCA) (4). The National Highway System (NHS) Designation Act of 1995 specifically required States to conduct LCCA on NHS projects costing $25 million or more (5). Although the 1998 Transportation Equity Act for the 21st Century (TEA-21) removed the requirement, interest in LCCA continues (5). The economics of sustainable development have led the design and construction industry to focus on long-term solutions (6). LCCA techniques are being applied to evaluate bridge decisions now. For example, Ehlen (7) examined the life-cycle cost-effectiveness of three fiber-reinforced-polymer (FRP) bridge decks, using LCCA for comparing new materials with conventional ones. Frangopol et al. (8) described the relationship between structural reliability in bridge engineering and life-cycle costing.

1.4 Research Approach

Initial research activities involve the identification and evaluation of nondestructive testing method for assessing the condition of concrete bridge elements. Based upon initial findings, the research focused on decision-making for treating corrosion and delamination of bridge decks. In this regard, the research extends the work of Babaei et al. (4) on the development of a mechanistic deterioration model and a methodology for estimating service life of concrete decks with chloride-induced corrosion through five specific contributions.

The method of Babaei et al., requires a threshold value for the maximum tolerable condition that represents current practice. Furthermore, the maximum tolerable condition for project-level decisions should be consistent with network-level recommendations. First, this research established a procedure for determining the maximum tolerable condition of bridge decks using the element-level inspection data collected from network-level bridge management system analyses.

Second, agencies must estimate the service life of treated concrete. This research presents a modification to the estimated service life equation of Babaei et al. (4) to correspond with the observed service lives of common treatments. The procedure is illustrated with a case study for a concrete bridge deck in Wisconsin.

Third, this research presents a set of alternative life-cycle treatment scenarios for concrete bridge decks and offers distribution functions for estimated unit costs.

Fourth, a probabilistic LCCA that assesses the economic risk of uncertain service life as a function of corrosion rate and uncertain agency costs is presented. Monte Carlo simulations are implemented to evaluate the risk distribution of alternatives.

Finally, a computerized spreadsheet application that implements a mechanistic model for deck deterioration and a probabilistic life-cycle cost analysis of alternative maintenance strategies is developed. The approach integrates project and network level decision-making and is illustrated with case studies from the Wisconsin DOT bridge inventory.

CHAPTER 2. DETERIORATION MODELING AND LCCA OF MAINTENANCE SCENARIO FOR CONCRETE BRIDGE DECKS

2.1 Overview of Methodology

In this research, an existing mechanistic model of concrete deterioration (4) was used to determine the performance and to estimate the service life of concrete bridge decks. A performance curve, i.e., a relationship between the condition index, S, and the age of the concrete, is computed to estimate the performance of the concrete over time. The performance equation used in the methodology (4), which represents S-shaped curves, is shown below.

$$S_t = 100 / [1 + A \exp(-Bt)] \qquad \text{(Equation 1)}$$

where

St = concrete condition index predicted for concrete age of t.

A, B = constants controlling the rate of deterioration and the shape of the curve.

t = time since initial construction (age of concrete)

Parameters A and B are a function of the condition of the deck. The condition of the concrete is quantified in terms of a condition index (S) that depends on three main factors: the percentages of spalled and delaminated areas and the chloride content at the bar level. Equation 2 shows the proposed relationship between these factors and the condition index S:

$$S = [\ CL + 2.5\ (DELAM) + 7.5\ (SPALL)\ ] / 8.5 \qquad \text{(Equation 2)}$$

$$\text{and } 0 < S <= 100$$

where

S = concrete condition index at the time of condition survey.

CL = percent of concrete samples with bar-level chloride content higher corrosion threshold value (0.035 percent of concrete weight (1.4 pounds per cubic yard)).

DELAM = percent of concrete area (not including spalls) that is delaminated.

SPALL = percent of concrete area that is spalled.

8.5 = a normalizing factor.

Figure 1 shows schematically the typical form of the performance curve obtained using this model. As a concrete deck ages and deteriorates, its condition index increases to a point that the concrete must be repaired or replaced. This point defines the maximum tolerable index, which is denoted as S_m.

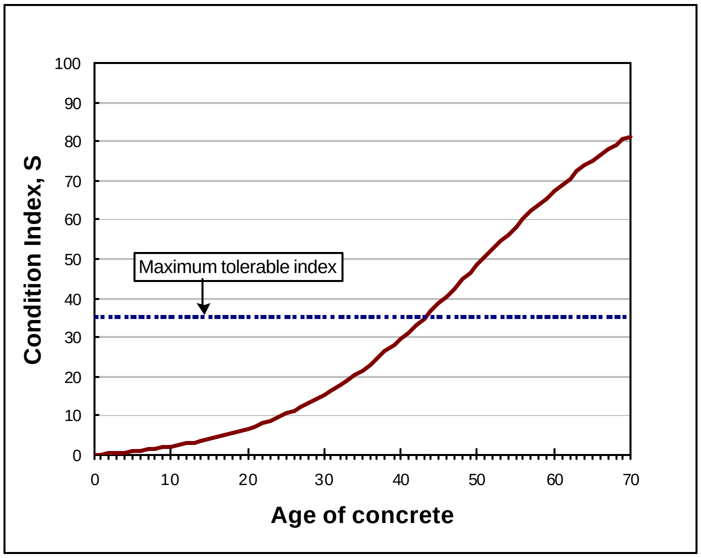


Figure 1. Typical performance curve (4)

The selection of the optimal treatment or maintenance depends, among other factors, on the estimated service life and the timing to perform the treatment. In the model, the estimated service life of a treatment is dependent upon a K factor, which represents the change in the rate of corrosion as a result of maintenance. The K factor may vary between 1 and -∞, with lower values representing a greater effectiveness of the treatment in decreasing the rate of corrosion (4). Currently, the selection of appropriate values of K requires considerable engineering judgment, since data that correlate the type of treatment and the corresponding reduction in the rate of corrosion are lacking.

2.2 Relationship between Maximum Tolerable Condition Index and Element-Level Condition State

Currently, routine element level inspections are conducted using the PONTIS bridge management system in Wisconsin. To apply the mechanistic model using the existing inspection data, a relationship between the model's condition index (S) and the PONTIS condition state index (PONTIS CSI) must be established. As described earlier, the condition index S is a function of the percentages of spalls, delaminations, and the bar-level chloride content in the concrete (4). On the other hand, the PONTIS CSI is a function of the percentages of spalls and delaminations combined. Therefore, S and PONTIS CSI cannot be correlated vis-à-vis, but they can be approximately mapped on a case-by-case basis as described below.

In this study, the data obtained from two bridge decks in Wisconsin (B-35-10 in District 7 and B-41-43 in District 5) were used to establish a relationship between S and PONTIS CSIs. These bridges were selected because they were the only bridges for which chloride content data were available at the time of this study. The data for these bridge decks are summarized in Appendix A.

2.2.1 Bridge B-35-10

The 1999 inspection report for this bridge indicated that the deck had no spalled areas, but that had 26.4 percent delamination (based on chain drag). The PONTIS CSI corresponding to this percentage of delamination is 5. The chloride content at the bar level was measured at five locations that same year. Based on this information, the estimated performance curve for the deck is shown in Figure 2.

It must be mentioned that in 1997, the same deck was assigned a PONTIS CSI of 4. A concrete overlay was recommended at the time, but it was not performed. Typically, a PONTIS CSI of 4 or higher indicates that the element has deteriorated to a point where it should be repaired or replaced, i.e., it would represent the maximum tolerable condition for the element in Wisconsin. From Figure 2, the condition index S in 1997 is approximately 17 (when a PONTIS CSI of 4 was assigned) and about 20 in 1999 (for a PONTIS CSI of 5).

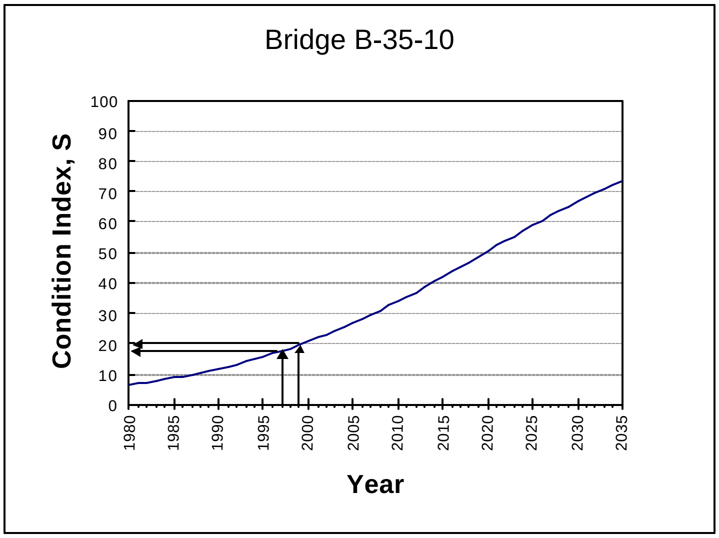


Figure 2. Performance curve of bridge deck B-35-10

2.2.2 Bridge B-41-43

This deck was given a PONTIS CSI of 4 in the year 2000 inspection report. Unfortunately, the total distressed area, the specific percentages of spalled or delaminated areas were not available and thus these percentages had to be estimated. Chloride content data at the bar level, however, were available at six locations for this deck. Based on past experience and estimates obtained from Wisconsin DOT bridge maintenance engineers, it was assumed that the ratio of spalled to delaminated areas is 1 to 3; that is 25 percent of the distressed area was spalled and 75 percent was delaminated. It must be noted that a PONTIS CSI of 4 corresponds to a percentage of combined spalled and delaminated areas between 10 and 25 percent. Two performance curves were then calculated to obtain estimates of the maximum tolerable index that represented the lower and upper bounds of a PONTIS CSI of 4 (i.e., 10 and 25 percent of distressed area). The calculated performance curves are shown in Figure 3. The figure shows that, for a condition state 4, the condition index S for this bridge deck ranges between 16 and 23 in year 2000.

Based on the calculated condition indices S for these two bridge decks, it follows that maintenance of bridge decks in Wisconsin is recommended when they reach a condition index S (or a maximum tolerable condition index) between 16 and 23. It must be noted that this range of values for S is lower than the maximum tolerable condition index of 35 suggested by Babaei et al. (4). In effect, a condition index of 35 represents approximately 50 percent of deteriorated concrete (spalled and delaminated) (4), whereas a PONTIS CSI of 4 represents a maximum of 25 percent of distressed area of concrete.

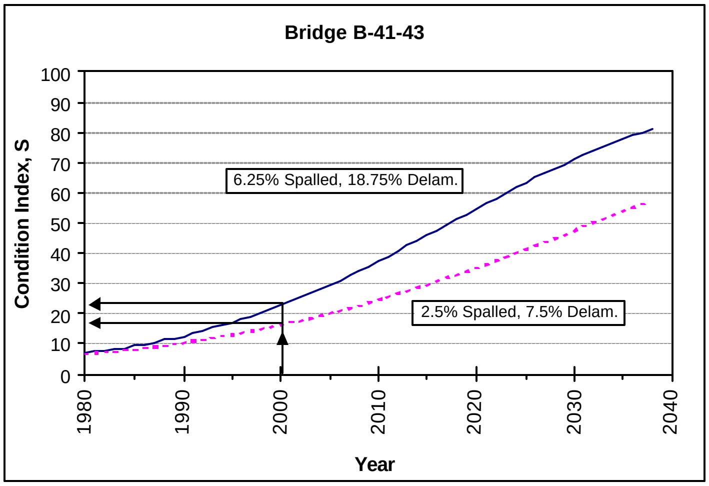


Figure 3. Performance curve of bridge deck B-41-43

2.3 Calibration of Estimated Service Life Equation of Treatments

The effectiveness of the treatment is quantified by the use of a parameter K in the mechanistic model. K represents the change in the rate of corrosion as a result of maintenance and is defined as “the ratio of the slope of corrosion rate increase after treatment to the slope of corrosion rate increase before treatment” (4). If the rate of corrosion continues to increase at the same rate (constant acceleration) after maintenance, then K = 1. If the rate of corrosion continues to increase after maintenance, but at a slower rate (less acceleration), K is between 0 and 1. Most commonly used treatments nowadays such as patching, asphalt and concrete overlays fall into this category. If the rate of corrosion decreases after the treatment, then K < 0, and if the rate of corrosion drops to zero after the treatment, K is -8.

The estimated service life of a treatment or maintenance is dependent not only upon the value of K, but also upon the time when the deck is expected to reach its maximum tolerable index (t_m), the time at the first sign of corrosion (t_0), and the time when the treatment is performed (t^*). The equation suggested by Babaei et al. (4) to estimate the service life of a treatment based on these parameters is as follows:

$$ESL = \{[(t^* - t_0)^2 + K (t_m - t_0)^2]^{0.5} - (t^* - t_0) \} / K \qquad \text{for K ? 0} \qquad \text{(Equation 3)}$$

$$ESL = 0.5\ (t_m - t_0)^2 / (t^* - t_0) \qquad \text{for } K = 0 \qquad \text{(Equation 4)}$$

where

ESL = estimated service life

t* = age of concrete at time of treatment

tm = age of concrete at maximum tolerable index (Sm)

t0 = age of concrete at time to first sign of corrosion

K = the ratio of the slope of corrosion rate increase after treatment to the slope of corrosion rate increase before treatment

In Figure 4, the estimated service life calculated of possible treatments (represented by different values of K) is shown for selected ages of the concrete at the time of treatment after the first sign of corrosion (i.e., selected values of $t^* - t_0$). These curves were constructed assuming that the maximum tolerable condition index, S_m, is reached 5 years after the first sign of corrosion (i.e., $t_m - t_0 = 5$ years). The figure shows that the later the treatment is done (i.e., a large value of $t^* - t_0$), the shorter the service life of the treatment. The figure also shows that K has very little impact on the estimated service life when maintenance is deferred. Also, positive values of K (i.e., less efficient treatments) have less impact on the service life than negative values (i.e., treatments that are more effective at reducing the corrosion rate).

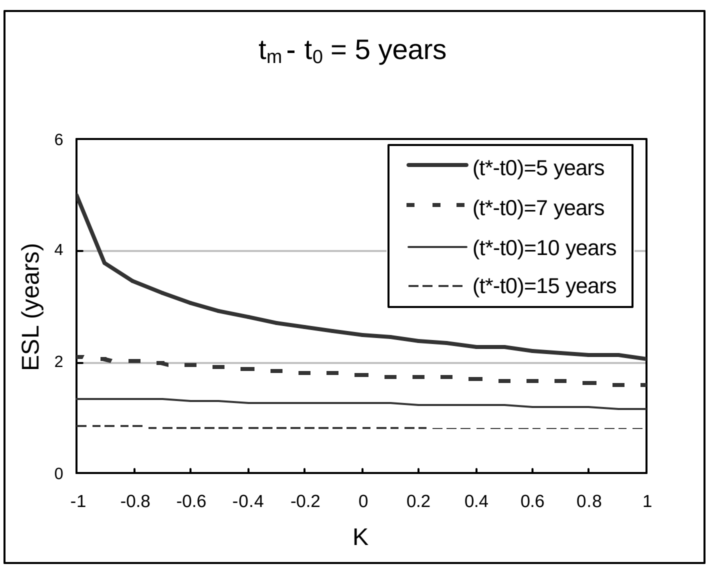


Figure 4. Estimated service life as a function of K and timing of maintenance

In Table 5, values of K for three common treatments (AC overlay without membrane, AC overlay with membrane, and concrete overlay) are shown. These values were chosen based on the suggested range of values for these types of treatments (4). The estimated corresponding service lives of these treatments calculated using Equations 3 and 4 are also shown in the table. These were calculated assuming that the treatment was done as soon as the concrete reached its maximum tolerable condition (i.e., $t^* = t_m$). Based on WisDOT's experience, it was also assumed that the time to reach the maximum tolerable condition after the first sign of corrosion was 5 years (i.e., $t_m - t_0 = 5$ years).

Also shown in Table 5 are the observed service lives for the treatments in Wisconsin. A comparison of the calculated and observed service lives is shown in Figure 5. The data shown in Table 5 and Figure 5 show that the observed service lives of the treatments are significantly underestimated by Equations 3 and 4.

Table 5. Service lives of maintenance actions ($t_m - t_0 = t^* - t_0 = 5$ years)

Maintenance actions	K factor	Estimated service life (years)	WisDOT observed service life (years)
AC overlay w/o membrane	1	2.07	2~3
AC overlay w/ membrane	0.7	2.17	7
Concrete overlay	1/8	2.44	15~20

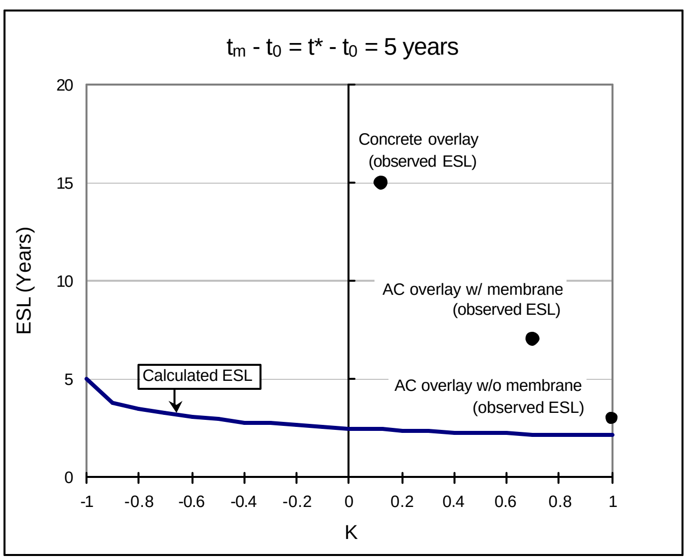


Figure 5. Comparison between estimated and WisDOT observed service lives of common treatments

In the absence of scientific or historical data on the reduction of the rate of corrosion for specific treatments, it was decided to apply a calibration factor to Equation 3 so as to match the observed and calculated service lives of treatments for the suggested values of K. Following this approach, a modified equation for concrete decks in Wisconsin is proposed:

$$ESL = \{[(t^* - t_0)^2 + K\,(t_m - t_0)^2]^{0.5} - (t^* - t_0)\} / K * (-5.37 * K + 6.88) \quad \text{for K?0} \qquad \text{(Equation 5)}$$

$$ESL = 0.5\,(t_m - t_0)^2 / (t^* - t_0) * 6.88 \qquad \text{for } K = 0 \qquad \text{(Equation 6)}$$

In Figure 6, the service lives of the treatments calculated with the modified equation are compared with those observed in practice (shown as solid dots). The corresponding curve computed with the original equations 3 and 4 is also shown in the figure for comparison. Figure 6 shows that the modified equations provide a very good match to the observed values while they retain the salient characteristics of the original model. Clearly, additional data are required to verify the validity of the modified equation for other treatment types, but a similar approach can be used to validate this equation in the future.

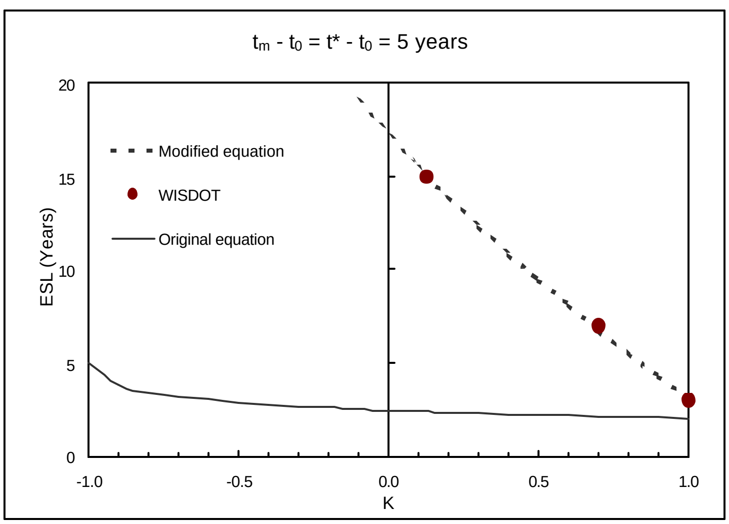


Figure 6. Comparison between estimated and observed service lives using the modified and original equations

Figures 7 and 8 illustrate the calculated service lives for increasing ages of concrete at the time of treatment, t^*, and for two ages of concrete at the maximum tolerable index, t_m (both parameters t^* and t_m are expressed in terms of t_0 as before). These figures show that the calculated service lives follow the same trend as that of the original equations (shown in Figure 4) but with values that are more realistic and consistent with the expected lives of common treatments. Notice that the longer the time required to reach the maximum tolerable index (larger t_m-t_0), the longer the estimated service life of the treatment is (as shown in Figures 7 and 8). This result reflects the influence of the quality of the existing concrete of the deck. A concrete deck of better quality is expected to last longer than that of poor quality. Thus, a treatment performed on a better quality concrete would be expected to have a longer service life than that on a poor quality concrete. An exception to this result occurs, however, when the entire deck is replaced. In such a case, Equation 5 or 6 do not apply as the estimated service life of a new deck is independent from the past maintenance history. In addition, epoxy-coated reinforcement is currently used in new deck designs. The service life of decks with epoxy-coated bars is unknown. However, current decks with epoxy coated bars have been virtually maintenance free for 20~25years in Wisconsin. Based on the recommendations and discussions with the Project Committee, it was decided to model the performance curve of new decks as the performance curve of a deck with black steel prefixed with 25~35 years of no deterioration (i.e., a maintenance free period).

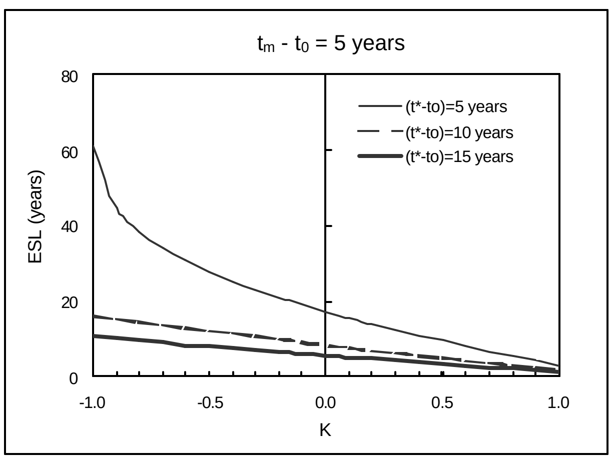


Figure 7. Estimated service lives as a function of the effectiveness of the treatment (K) using the modified equations (t_m - t_0 = 5 years)

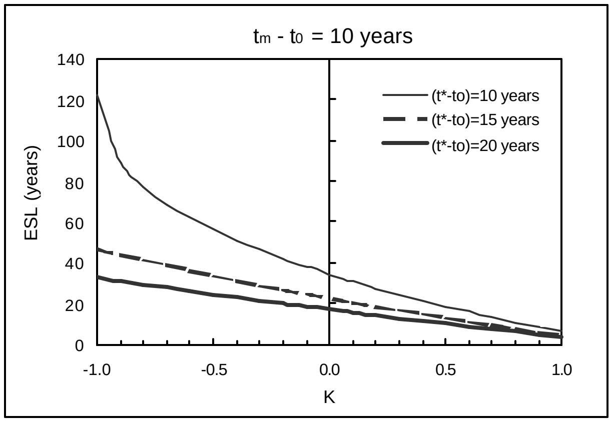


Figure 8. Estimated service lives as a function of the effectiveness of the treatment (K) using the modified equations (t_m - t_0 = 10 years)

Equations 5 and 6 were calibrated based on the treatment timing in Wisconsin, which is the time when the deck reaches its maximum tolerable condition S_m. The range of values for S_m for bridge decks in Wisconsin was determined to be between 16 and 23 in section 2.2. Therefore, Equations 5 and 6 are applicable when S_m is within that range, 16 to 23. For other values of S_m, the equation of estimating service life of treated concrete can be calibrated through the same procedure proposed in this section.

2.4 Performance Curve after Treatment

The performance curve after treatment is calculated using Equation 1 by re-computing parameters A and B for the condition index of the treated deck.

The condition index after the treatment is calculated from Equation 2, as before, using the estimated chloride content and the spalled and delaminated areas immediately *after* the treatment as follows.

Unless chloride extraction is performed, the chloride content on the existing concrete may be assumed to be the same as that just before the treatment. The latter may be estimated from the following equations (4).

$$CL = 5\,S \quad \text{but} \quad <= 100 \text{ (percent)} \qquad \text{(Equation 7)}$$

where S is the condition index at the time of the treatment (from Equation 1).

For example, the amount of chloride content at the time of treatment for a condition index S = 23 is calculated as follows.

$$CL = 5 * 23 = 115 > 100, \text{ therefore, } CL = 100\ (\%)$$

The percent of delaminated and spalled areas immediately after the treatment will depend upon the treatment considered. For a concrete overlay, for example, it may be assumed that all delamination and spalls are repaired but that chlorides are not removed from the existing concrete. Therefore, after performing a concrete overlay, the amount of chloride content, delaminations, and spalls would be 100%, 0%, 0%, respectively. For other treatments, such as patching and AC overlay, it may be assumed that all spalls are repaired and 50% of the delaminated area existing at the time the treatment remains in the concrete. To estimate the percentage of delaminated and spalled areas just before the treatment is done, the following equation may be used.

$$DELAM = (8.5\ S - CL) / (2.5 + 7.5 / N) \qquad \text{(Equation 8)}$$

where

N = ratio of DELAM to SPALL just before the treatment is done. In Babaei et al. (4), for all deck concrete except those with 1 inch, or thicker, concrete overlays: DELAM is 4 times SPALL. For all deck concrete with 1 inch, or thicker, bonded concrete overlay: DELAM is 8 times SAPLL. In this application, the ratio of DELAM to SPALL is assumed 3, based on past experience and estimates obtained from Wisconsin DOT bridge maintenance engineers.

SPALL = DELAM / N

For example, the amount of delaminated and spalled areas at the time of treatment for a condition index S = 23 are calculated as follows.

$$DELAM = (8.5 * 23 - 100) / (2.5 + 7.5 / 3) = 19.1\ (\%)$$

$$SPALL = 19.1 / 3 = 6.37\ (\%)$$

The condition index after a concrete overlay is done would be

$$S = [\ 100 + 2.5\ (0) + 7.5\ (0)\ ] / 8.5 = 11.8$$

For an AC overlay, the condition index would be

$$S = [\ 100 + 2.5\ (0.5 * 19.1) + 7.5\ (0)\ ]\ /\ 8.5 = 14.6$$

Figure 9 shows the performance curves for the existing deck and the treated concrete after a concrete overlay is done.

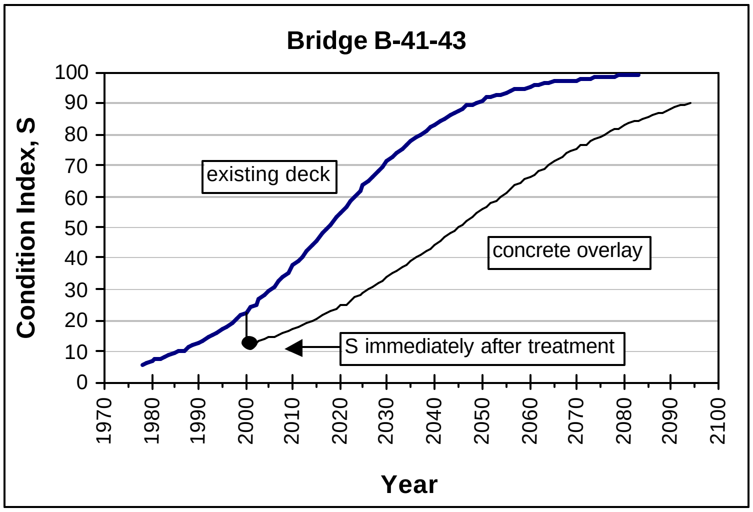


Figure 9. Performance curves, before and after the treatment

2.5 Maintenance Strategies and Scenarios

The optimal performance of maintenance depends not only upon timing of the action but also upon the effectiveness of the treatment itself. The ability to reduce the rate of corrosion in concrete varies from treatment to treatment. A set of alternative life-cycle scenarios that are routinely used by state and local transportation agencies or that offer potential economic and practical benefits are identified and listed below. For each scenario, a semicolon delimits treatments and the series of treatments in brackets are assumed to be repeated until the end of the analysis period.

1. New construction; [concrete overlay; deck replacement]
2. New construction; [patching; patching; patching; deck replacement]
3. New construction; [patching; patching; patching; asphaltic concrete (AC) overlay; deck replacement]
4. New construction; [asphaltic concrete overlay with membrane]
5. New construction; [deck replacement]

6. New construction; chloride extraction and patch; [chloride extraction]

7. New construction; chloride extraction and concrete overlay with corrosion inhibitor in the mix; [spray corrosion inhibitor]

8. New construction; patching; [cathodic protection]

Scenarios 1 through 5 are familiar to bridge maintenance engineers. Scenarios 6 and 7 include the application of relatively new technologies (chloride extraction and corrosion inhibitors), which may offer potential economical and practical benefits. Scenario 8 considers the use of cathodic protections, a technique that is not new, but that is infrequently used by DOTs.

In Scenario 6 (chloride extraction and patching; [chloride extraction]), the spalled concrete is removed, chlorides are extracted, and the area is patched. The scenario assumes that the deck undergoes periodic chloride content testing and repeated chloride extraction as needed. Chloride extraction is more formally referred to as Electrochemical Chloride Extraction (ECE). By keeping chloride ions away from the steel reinforcement, the pH of the concrete passivates the reinforcement and prevents corrosion. Most codes accept 0.2-0.4% chlorides by weight of cement in new, ordinary reinforced concrete. These values are also considered to be acceptable for concrete that has been the treated (9). For additional protection, a chloride resistant sealant or a waterproof membrane may be applied after the treatment has been completed.

Field test results indicate that chloride extraction is effective for ten years or more (10). If the structure is protected with a sealant after treatment, there is a low possibility that corrosion will further develop. If the structure is not sealed, chloride may contaminate the element again, and a new treatment will probably be required in another 10-15 years (11). ECE of prestressed concrete structures is presently not recommended due to hydrogen production, resulting in embrittlement of high strength steel (9).

In Scenario 7 (Chloride extraction and concrete overlay with corrosion inhibitor in the mix; [spray corrosion inhibitor]), a layer of an existing concrete deck including delaminated areas is removed, chlorides are extracted, and the deck is overlaid with concrete that has a corrosion inhibitor in the mix. The deck surface is periodically treated with a migrating corrosion inhibitor (MCI). Corrosion inhibitors have been used as an admixture in the fresh concrete mix. Depending on how they affect the corrosion process, corrosion inhibitors are categorized as anodic, cathodic, or mixed (12). By supplying more active anions to react with the ferrous ions (so called anodic inhibitors) or more active positrons to react with the chloride ions (so called cathodic inhibitors), corrosion inhibitors stop interactions between chloride and ferrous ions thus preventing concrete elements from corroding.

More recently, migrating corrosion inhibitors (MCIs) have been developed that can be used not only as an admixture, but also for surface impregnation (13). MCIs are mixed cathodic and anodic corrosion inhibitors. Under normal conditions these substances enhances the vapor pressure. Increased pressure causes the inhibitors molecules to diffuse through the concrete. Once the MCIs migrate to the rebar's surface, a monomolecular protective layer is formed.

Corrosion inhibitors are new. Field studies (13, 14, 15) are inconclusive as to the effectiveness and reliability of corrosion inhibitors and thus no service life are not available at this time.

Scenario 8 (patching; [cathodic protection]) includes constant treatment through a cathodic protection system. Cathodic Protection (CP) is based on changing the potential of the steel reinforcement to a more negative value and on reducing potential differences between anodic and cathodic sites. The method can reduce the corrosion current to negligible values and thus prevent corrosion from happening (16).

CP is an ongoing system; the current must continue to flow during the remaining service life of the structure. The CP system should be check monthly, and data should be analyzed to ensure that CP criteria are being met. At the same time, degradation of concrete around the anode may occur, which is only significant at high current densities. As with ECE, CP is not recommended for high strength steel because of potential embrittlement (16).

These eight scenarios describe the life-cycle strategy for existing bridges. Except in extreme situations, Scenario 8 is considered too expensive and impractical. Table 6 shows the expected service lives, cost ranges and productivities of the treatments based on data provided by bridge maintenance engineers of the Wisconsin DOT. Due to the lack of field experience and data for chloride extraction, corrosion inhibitors, and cathodic protections, K factors and costs are not available at this time and thus excluded from Table 6. Addition data is required for the implementation of these three scenarios.

Table 6. Estimated costs and productivity of concrete deck treatments (provided by WisDOT)

Treatment	Estimated Service Life (years)	District 1			District 5			Includes Traffic control	Includes Concrete Preparation	Note
		Cost Range ($)	Unit	Productivity	Cost Range ($)	Unit	Productivity			
Patching					10 ~ 20	ft^2		Yes	Yes	
		1.75 ~ 2.5	ft^2	16 ft^2 / 0.5 day				No	No	
Patching with conquest rust inhibitor applied		2.75 ~ 3.5	ft^2	16 ft^2 / 0.5 day				No	No	
AC overlay w/o membrance	2 ~ 3				5	ft^2		Yes	Yes	
		15 ~ 17	yd^2	40'*150' / day				No	Yes	
AC overlay w/ membrance	7				5 ~ 10	ft^2		Yes	Yes	
		18	yd^2	40'*150' / day				No	Yes	
Concrete overlay	15 ~ 20	27 ~ 31	ft^2	Average bridge / 3 weeks	10 ~ 20	ft^2	100ft *30ft / 30 days 200ft *30ft / 35~40 days	Yes	Yes	
		15 ~ 20	ft^2	Average bridge / 3 weeks				No	Yes	
Concrete masonry overlay					11	ft^3		No	No	1998 dollars
Removal of delaminated concrete		5 ~ 15	ft^2		4	ft^2		No	Yes	$4/$ft^2$ is in 1998 dollars
Application of sealer		0.05	ft^2		0.25 ~ 0.4	ft^2		No	No	
Full depth deck repair					19	ft^2		Yes	Yes	
Rehabilitation (redeck)	20				52	ft^2		Yes	Yes	
New deck		35 ~ 40	ft^2					Yes	N/A	

2.6 Reliability-Based Life-Cycle Cost Analysis

In the life-cycle cost analysis, the agency unit cost and K-fators of treatments are treated as random variables with triangular distributions. Table 7 summarizes the recommended values for these variables as determined from the cost data provided by WisDOT (Table 6) and the suggested K-factors from Babaei et al. (4). The agency unit cost (dollars per square foot) includes surface preparation and traffic control. For new decks, the prefixed (offset) value is treated as a random variable.

User costs during the maintenance and in the years between maintenances are also included in the life-cycle cost analysis and are calculated based on the equations suggested by Babaei et al. (4). User costs during treatment are due to increases in travel time caused by a detour if the bridge is closed or by reduced speed on the bridge if the bridge remains open during construction. In years when no treatment is performed, user costs are due to the condition of the bridge deck and its effect on traffic flow.

In the life-cycle cost analysis, it is assumed that all past costs are sunk costs. Salvage value is based on the remaining service life at the end of the analysis period.

Table 7. Suggested range of unit agency cost, K values, and offset value of treatments

<table>
<tr><th rowspan="2">Item</th><th rowspan="2">Treatment</th><th colspan="3">Agency Unit Cost (dollars/ft^2)</th><th colspan="3">K-factor</th></tr>
<tr><th>min</th><th>most likely</th><th>max</th><th>min</th><th>most likely</th><th>max</th></tr>
<tr><td>1</td><td>Patching</td><td>10</td><td>15</td><td>20</td><td>0.9</td><td>0.95</td><td>1</td></tr>
<tr><td>2</td><td>Concrete overlay</td><td>25</td><td>30</td><td>35</td><td>0.05</td><td>0.125</td><td>0.2</td></tr>
<tr><td>3</td><td>AC overlay w/o membrance</td><td>4</td><td>5</td><td>6</td><td>0.9</td><td>0.95</td><td>1</td></tr>
<tr><td>4</td><td>AC overlay with membrance</td><td>5</td><td>7.5</td><td>10</td><td>0.65</td><td>0.7</td><td>0.75</td></tr>
<tr><td rowspan="3">5</td><td rowspan="3">Deck replacement with epoxy coated bars</td><td rowspan="3">35</td><td rowspan="3">37</td><td rowspan="3">40</td><td colspan="3">Offset (years)</td></tr>
<tr><td>min</td><td>most likely</td><td>max</td></tr>
<tr><td>25</td><td>30</td><td>35</td></tr>
</table>

To conduct a probabilistic LCCA, a Monte Carlo simulation is used. The Monte Carlo simulation provides a way to analyze the risk impact of uncertain and random variables on the results of the life-cycle cost analysis (5). In each iteration, values for random variables (unit agency cost, K factor of treatment, and offset value of deck replacement) are generated according to the triangular distribution in Table 7. Therefore, in the simulation, each iteration represents a possible set of values for one scenario. This process of sampling from a probability distribution is repeated until the specified numbers of iteration are completed or until the simulation process converges. The simulation process usually converges within 20 iterations for the cases studied in this report. In the application tool, 100 iterations are computed by default.

For the life-cycle cost analysis of bridge B-41-43, a value of S_m = 23 was used. The deck of bridge B-41-43 is estimated to reach the S_m of 23 in 2000. Treatments are assumed to be applied on-time when the deck reaches S_m. The analysis period is 70 years starting in year 1999 and 3% discount rate was used. For 100 Monte Carlo iterations, the average estimated service lives of treatments, and the range and average net present values (NPV) of total life-cycle cost are summarized in Table 8.

Table 8. Average ESL of treatments and NPV of life-cycle cost for maintenance when bridge deck B-41-43 reaches maximum tolerable condition (S_m=23)

Scenario	Treatment	Average ESL (years)	Range of NPV ($1,000)	Average NPV ($1,000)
Scenario 1	Concrete overlay	18	532 ~ 595	556
	Deck replacement	66		
Scenario 2	Patching	4	520 ~ 619	571
	Patching	4		
	Patching	4		
	Deck replacement	66		
Scenario 3	Patching	4	564 ~ 655	604
	Patching	4		
	Patching	4		
	AC overlay w/o membrane	6		
	Deck replacement	66		
Scenario 4	AC overlay w/ membrane	8	469 ~ 626	536
Scenario 5	Deck replacement	66	439 ~ 506	482

Based on the results of 100 iterations, a histogram of NPV of total life-cycle costs and a plot of cumulative probability of total life-cycle costs were obtained. Figure 10 shows the risk profile of the NPV of total life-cycle cost in histogram form. The risk profile shows the probability distribution of estimated life-cycle cost for each of the scenarios considered. The histogram shows the variability about the mean value. The wider the distribution is, the greater the variability is. Figure 10 shows that scenario 4 is the most uncertain and scenario 1 is the least uncertain.

Figure 11 shows the risk profiles for the different scenarios in the form of cumulative probability distribution of NPV of total life-cycle costs. The graph shows the probability that life-cycle cost is less than or equal to the value on the x-axis. The slope of the cumulative curve shows the range of variability. The steeper the slope, the lesser the variability is. In Figure 11, the curve for scenario 4 is the flattest and the curve for scenario 1 is the steepest one. Therefore, the life-cycle cost for scenario 4 is most variable and the life-cycle cost for scenario 1 is the least variable.

Since all scenarios provide the same benefit, that is to keep the bridge deck condition from exceeding the maximum tolerable condition, the optimal maintenance scenario is determined by the lowest NPV of total life-cycle costs. In this case, by comparing the average NPV of life-cycle costs, the order of scenarios is scenario 5, scenario 4, scenario 1, scenario 2, and then scenario 3.

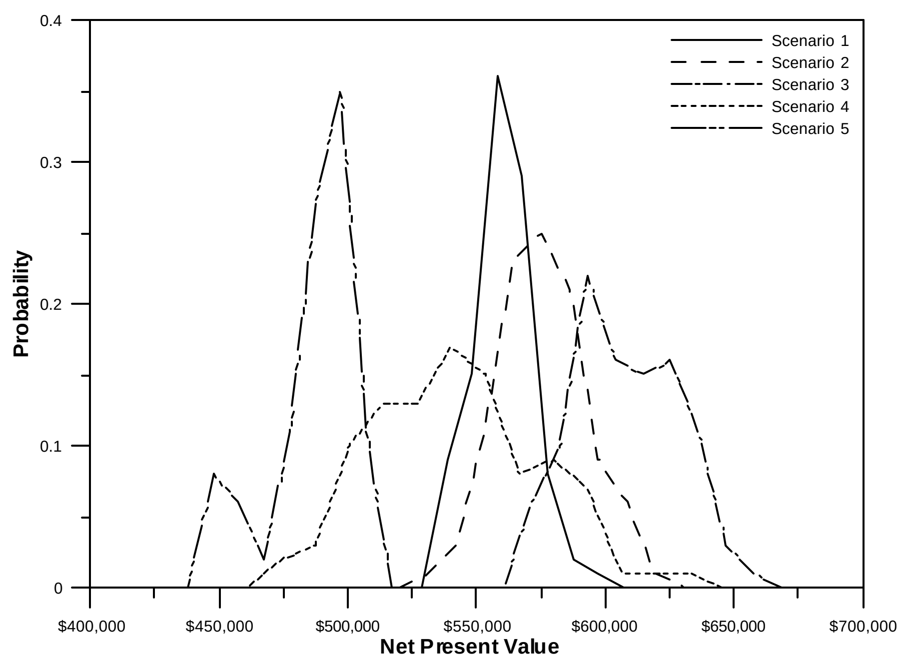


Figure 10. NPV of life-cycle cost for maintenance when bridge deck B-41-43 reaches maximum tolerable condition (S_m=23)

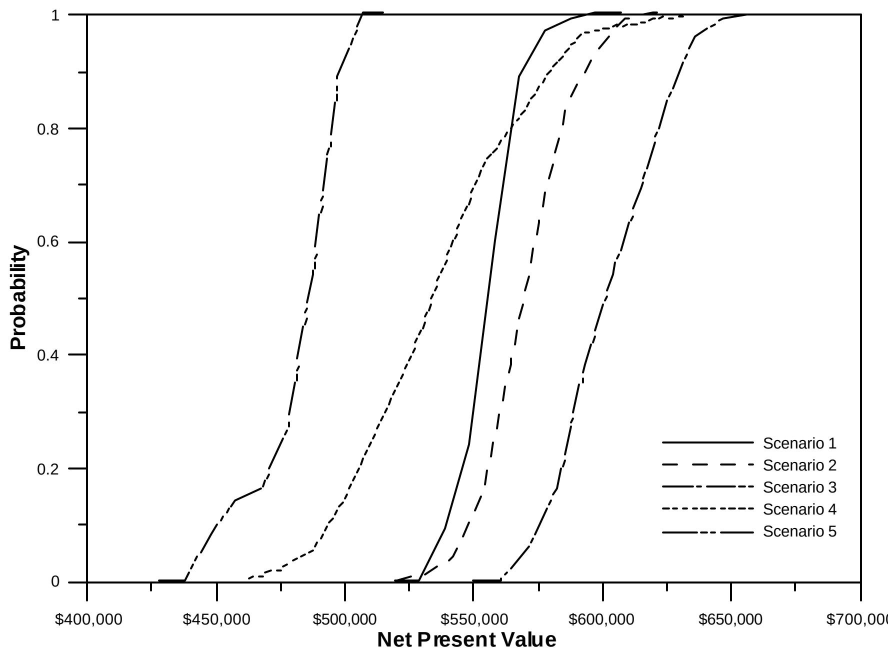


Figure 11. Cumulative probability of life-cycle cost for maintenance when bridge deck B-41-43 reaches maximum tolerable condition (S_m=23)

CHAPTER 3. INTERPRETATION AND SENSITIVITY OF MODEL PARAMETERS

Three main factors influence the results of LCCA: the agency unit cost of treatments, the service life of the treated concrete, and the discount rate. The service life of the treated concrete is influenced by the maximum tolerable condition index (S_m), and the effectiveness of the treatments to arrest corrosion (K-factor). This chapter examines these parameters to understand how they directly or indirectly influence the results of LCCA.

3.1 Influence of Agency Unit Cost of Treatments on Total LCC

In this study, agency unit costs of treatments are modeled as random variables with triangular distributions in the LCCA. To understand how agency costs influence the results of LCCA for each scenario, three values of cost were studied for each treatment: minimum, most likely, and maximum. When a maintenance scenario consisted of two or more different treatments, the agency unit cost was fixed for the treatment of interest while the cost of the other treatments was treated as a random variable. This procedure was then repeated for each treatment in a given scenario. The fixed agency unit costs for the treatment of interest are listed in Table 9. In this table, the treatment of interest is shown in bold face. The Monte Carlo simulation treated other costs and K-factor as random variables. The analysis focused on bridge B-41-43 with on-time maintenance at S_m of 23. The analysis period was 70 years starting in year 1999 and a discount rate of 3% was used.

Table 9 shows the expected total life-cycle cost for each scenario and the percentages of total cost attributed to agency cost of the treatment studied. The influence of agency cost of a treatment on the total life-cycle cost depends on the treatment type. The variation in patching costs can account for up to 16% of the total life-cycle cost. At the other extreme, the variation in agency cost of an AC overlay without membrane accounts for only one percent of the total life-cycle cost.

As shown in Figure 12, the percent of total life-cycle cost attributed to a treatment also depends on the scenario. When combined with other treatments, cost for deck replacement may account for 18 to 25 percent of the total life-cycle cost (see Table 9, 1b, 2b, 3c). As a stand alone treatment (Scenario 5), the agency cost for deck replacement may account for 42 to 47 percent of the total NPV of costs, with the remaining costs being attributed to user costs.

Table 9. NPV of total life-cycle costs for maintenance scenarios and percentage attributed to agency cost of treatments

Scenario*	Case	Unit agency cost of treatment of interest (dollars/ft^2)	Total NPV ($1,000)	% of total NPV attributed to treatment of interest
1a. [**concrete overlay**; deck replacement]	min.	25	527	26.6
	most likely	30	556	30.4
	max.	35	584	33.6
1b. [concrete overlay; **deck replacement**]	min.	35	549	18.0
	most likely	37	556	18.9
	max.	40	562	20.1
2a. [**patching; patching; patching;** deck replacement]	min.	10	497	30.1
	most likely	15	572	39.3
	max.	20	647	46.4
2b. [patching; patching; patching; **deck replacement**]	min.	35	562	22.8
	most likely	37	573	23.6
	max.	40	582	25.1
3a. [**patching; patching; patching;** AC overlay w/o membrane; deck replacement]	min.	10	528	28.0
	most likely	15	603	36.9
	max.	20	677	43.8
3b. [patching; patching; patching; **AC overlay w/o membrane;** deck replacement]	min.	4	596	2.5
	most likely	5	601	3.1
	max.	6	604	3.7
3c. [patching; patching; patching; AC overlay w/o membrane; **deck replacement**]	min.	35	591	19.1
	most likely	37	600	19.7
	max.	40	611	21.1
4. [**AC overlay w/ membrane**]	min.	5	474	26.7
	most likely	7.5	539	35.4
	max.	10	603	42.2
5. [**deck replacement**]	min.	35	473	42.7
	most likely	37	481	44.6
	max.	40	497	46.8

* Treatment of interest with fixed agency unit cost is shown in bold face.

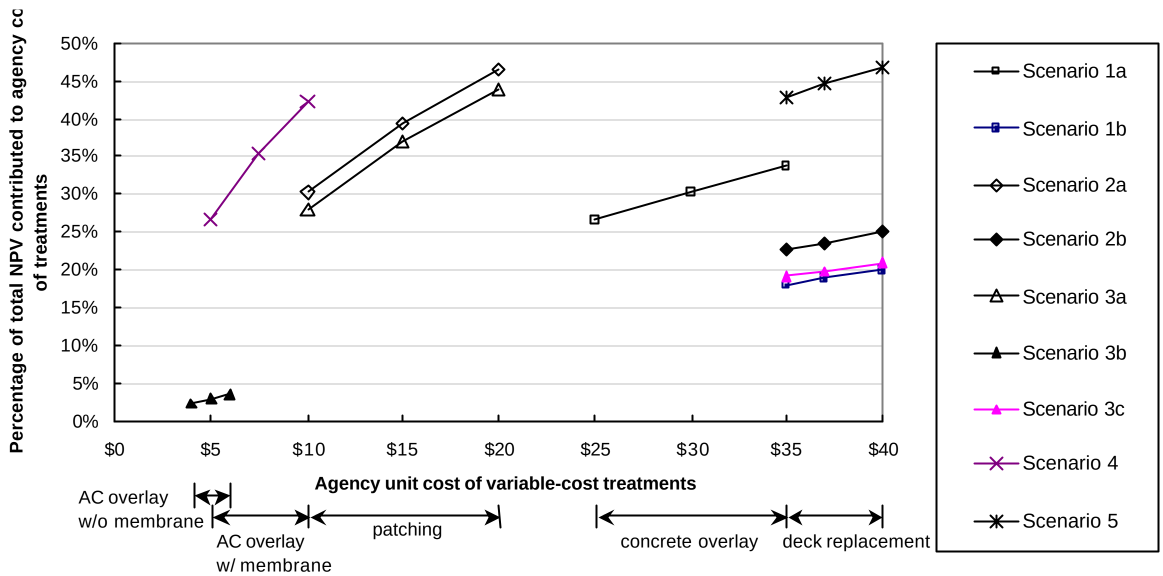


Figure 12. Percentage of total NPV attributed to agency unit cost of treatments

3.2 Influence of Maximum Tolerable Condition Index (S_m) on ESL of Treatments

In this section, the estimated service life of treatments are compared for maximum tolerable condition index (S_m) ranging from 23 and 35. The former value of S_m approximately corresponds to current practice in Wisconsin. The later value of S_m was recommended by Babaei (4).

In this analysis, K-factors of treatments were treated as random variables, and 100 Monte Carlo simulations were conducted. Table 10 and Figure 13 show the average estimated service life of treatments for different S_m. For this range of S_m, higher S_m (i.e., higher tolerable condition indices) leads to longer service lives of treatments. The curves in Figure 13 are not quite parallel because the K-factors were assumed as random variables.

Table 10. Estimated service life of treatments (years)

S_m	Concrete overlay	Patching	AC overlay w/o membrane	AC overlay w/ membrane	Deck replacement
23	18	4	4	8	66
24	19	4	4	9	67
25	20	5	5	9	68
26	21	5	5	10	69
27	23	6	6	11	70
28	24	6	6	12	71
29	25	7	7	13	72
30	26	7	7	14	72
31	27	8	8	15	72
32	28	9	9	17	74
33	29	9	9	18	74
34	29	10	10	19	75
35	30	11	11	21	76

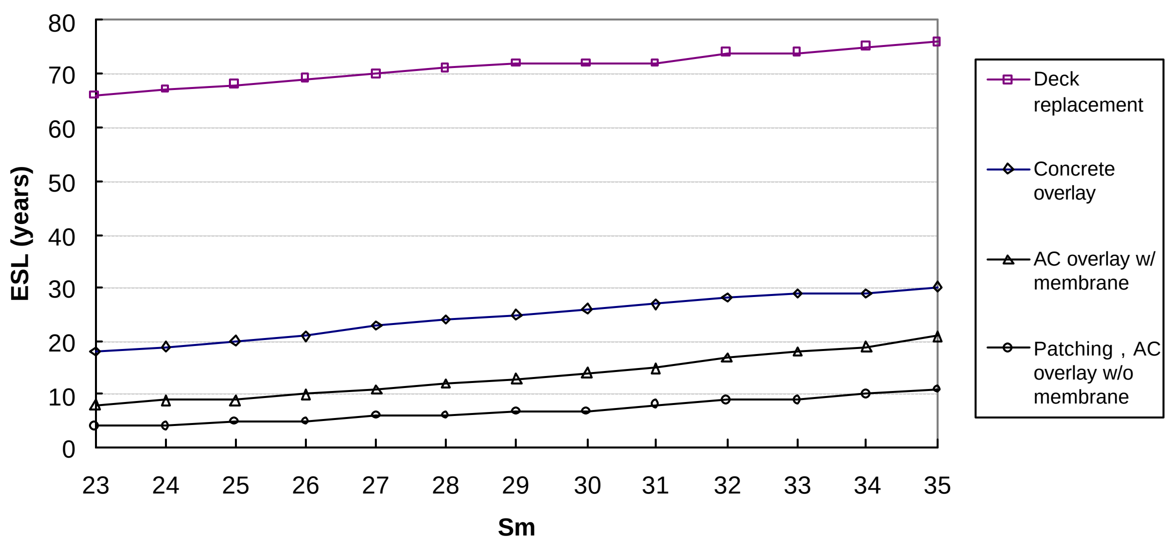


Figure 13. Effect of S_m on ESL of treatments

3.3 Influence of S_m on LCC

In this section, the life-cycle costs of scenario 4 (AC overlay w/membrane) are compared for different values of the maximum tolerable condition index (S_m) ranging from 23 and 35. The deck of B-41-43 is estimated to reach the maximum tolerable condition index of 23 in 2000 and 35 in 2009. The analysis period of LCCA was 70 years starting in 1999 and a discount rate of 3% was used.

The average estimated service lives of the treatment, agency costs, user costs, and the total life-cycle cost of scenario 4 (based on 100 Monte Carlo iterations) for different values of S_m are listed in Table 11. Figure 14 shows how cost varies as a function of S_m. The estimated service life of the treated concrete is longer for higher S_m. Longer service life leads to less frequent treatments and lower life-cycle agency cost and user cost during the treatments. However, agency cost savings are offset by increased user costs in the years between treatments.

As shown in Figure 14, the total life-cycle cost is a convex function of S_m. This means that there is a particular value of S_m that minimizes the total life-cycle cost. For the assumptions of this analysis, the minimum total life-cycle cost can be achieved at S_m = 29.

Table 11. Effect of S_m on life-cycle cost of Scenario 4 [AC overlay w/ membrane]

S_m	Average ESL (years)	NPV Agency cost ($1,000)	NPV User cost during treatments ($1,000)	NPV User cost in years between treatments ($1,000)	NPV Total cost ($1,000)	Standard deviation Total cost ($1,000)
23	8	187	265	81	533	34
24	9	162	233	97	492	29
25	9	152	206	115	473	30
26	10	135	192	132	459	28
27	11	123	174	152	449	29
28	12	105	161	170	436	19
29	13	96	145	190	431	23
30	14	91	137	206	434	17
31	15	86	119	245	450	20
32	17	72	110	268	450	16
33	18	70	108	283	461	15
34	19	63	95	321	479	10
35	22	55	89	353	497	19

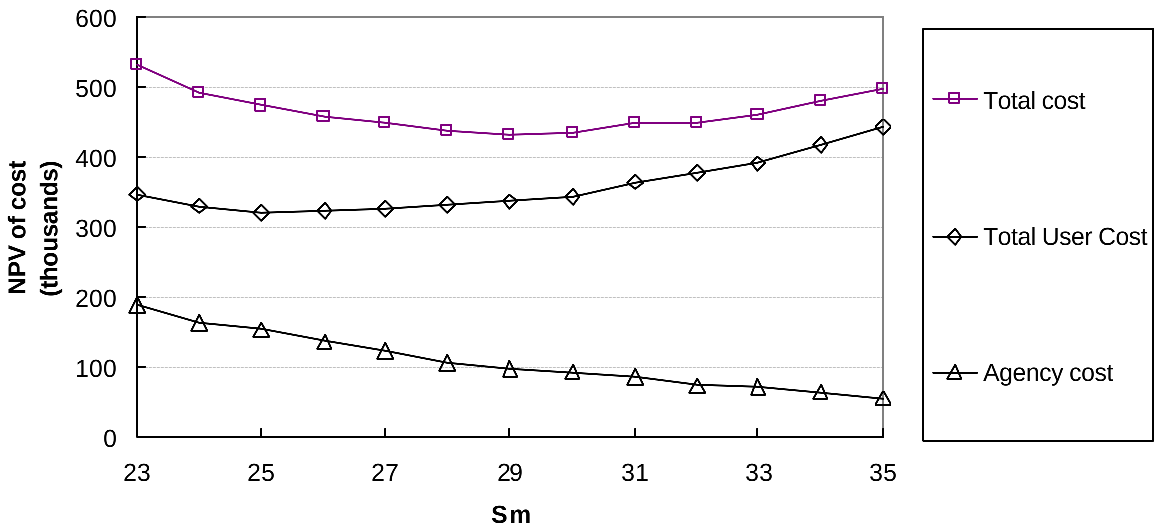


Figure 14. Effect of S_m on user and agency component of total cost (Scenario 4)

3.4 Influence of Treatment Effectiveness to Arrest Corrosion (K-factor) on ESL of Treatments

K-factor represents the change in the rate of corrosion of an existing deck as a result of maintenance. If the rate of corrosion continues to increase at the same rate (constant acceleration) after maintenance, then K = 1. If the rate of corrosion continues to increase, but at a slower rate (less acceleration), then K varies between 0 and 1. Most commonly used treatments such as patching, asphalt, and concrete overlays all fall into this latter category. In the analysis, K-factor is modeled as a random variable with triangular distribution. The ranges of K-factor for the treatments in scenarios 1 to 5 are shown in Figure 15. Note that the ranges of K-factor for patching and AC overlay w/o membrane are the same; however, the agency unit costs of these two treatments are different as shown in Table 7.

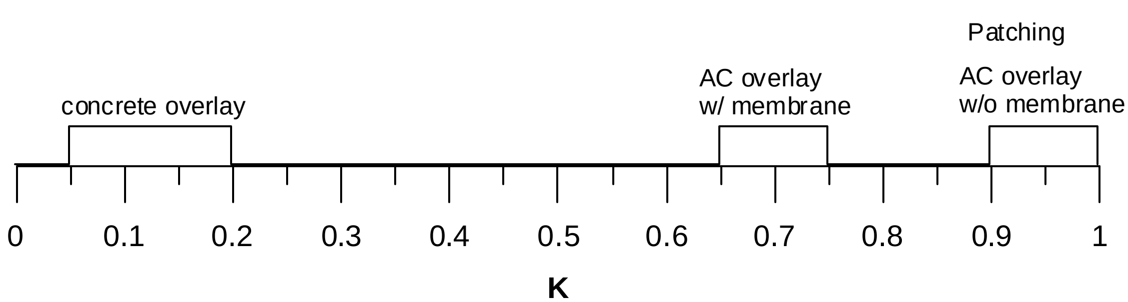


Figure 15. Ranges of K factors of treatments

The K-factor influences the estimated service life of a treatment and consequently the results of LCCA. To understand how the K-factor influences the ESL, three values of the K-factor: minimum, most likely, and maximum values are compared. Four treatments are examined: patching, concrete overlay, AC overlay without membrane, and AC overlay with membrane.

Deck replacement is not examined because the estimated service life of a deck replacement is not modeled by the K-factor. Rather, the estimated service life of a replacement deck is measured directly from the performance curve after the treatment. The performance curve after treatment is modeled as an offset followed by the original performance curve of the deck. The offset value indicates the amount of time before the epoxy-coated bars in the deck begins to deteriorate. The offset value is modeled as a random variable with triangular distribution in the LCCA.

Figure 16 shows the range of ESL of deck B-41-43 at S_m = 23 for different treatments. Treatments with lower K-factors have a better ability to reduce the corrosion rate. Therefore, the estimated service life of treatments with lower K-factors is longer. It should be noted that K-factor does not model the durability of the treatments; e.g. ability to withstand wear and tear. For the maintenance treatments considered, ESL is based upon observed values. K factors were calibrated to include durability.

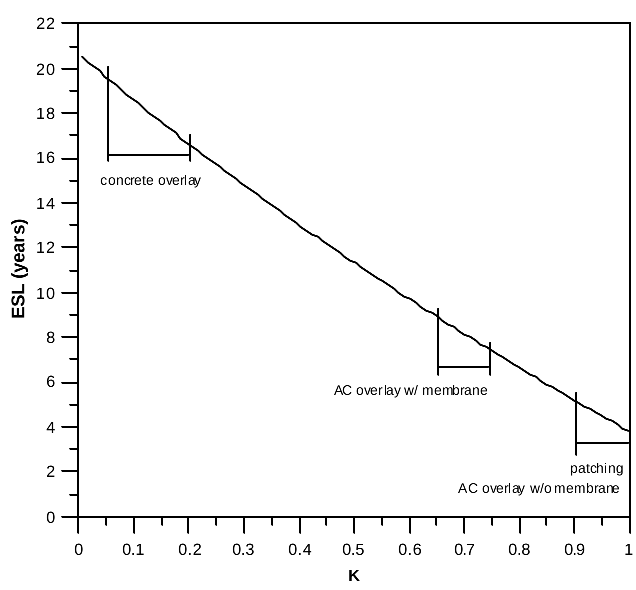


Figure 16. Service life of treatment for different K factors (B-41-43 at S_m = 23)

3.5 Influence of Discount Rate

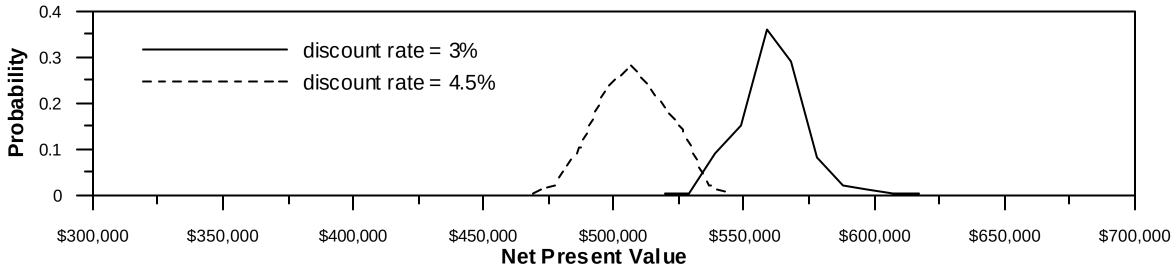
This section compares the life-cycle costs for the five maintenance scenarios for two different values of discount rate: 3% and 4.5%. Wisconsin uses 3%, and Minnesota uses 4.5% (17). The analysis focuses on B-41-43 with on-time maintenance at S_m = 23.

Table 12 compares the NPV of life-cycle cost for maintenance using both discount rates. As shown, NPV of maintenance decreases when discount rate increases. The decrease is especially noticeable for scenario 4, where costly treatments are performed later in the life-cycle.

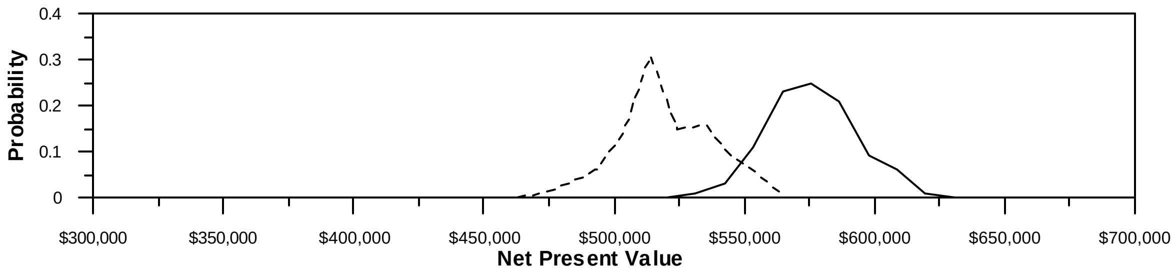
Figure 17 compares the histograms of total life-cycle cost for each scenario. In all cases, higher discount rate yields lower expected NPV of life-cycle cost. The decrease of NPV due to higher discount rate depends upon the scenario because treatments occur at different times during the life-cycle for each scenario. When 4.5% discount rate is used, scenario 4, instead of scenario 5, is the one with the lowest life-cycle cost.

Table 12. Expected total NPV of life-cycle cost ($1,000) for maintenance using discount rates of 3% and 4.5% (B-41-43, S_m=23)

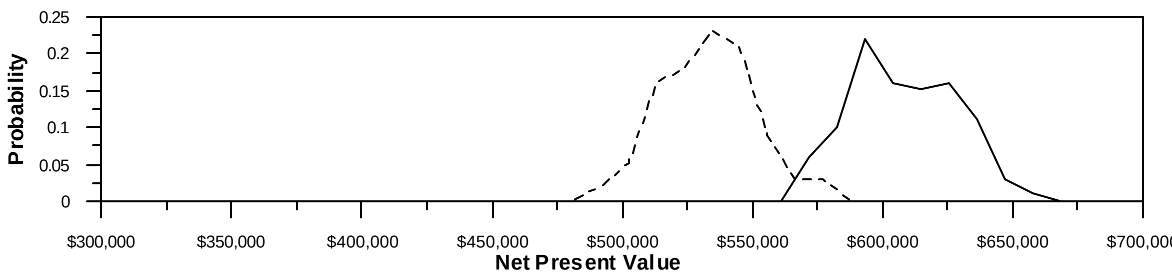
Scenario	Total expected life-cycle cost ($1,000)	
	Discount rate = 3%	Discount rate = 4.5%
1. [Concrete overlay; deck replacement]	556	502
2. [Patching; patching; patching; deck replacement]	571	514
3. [Patching; patching; patching; AC overlay w/o membrane; deck replacement]	604	528
4. [AC overlay w/ membrane]	536	394
5. [Deck replacement]	482	455



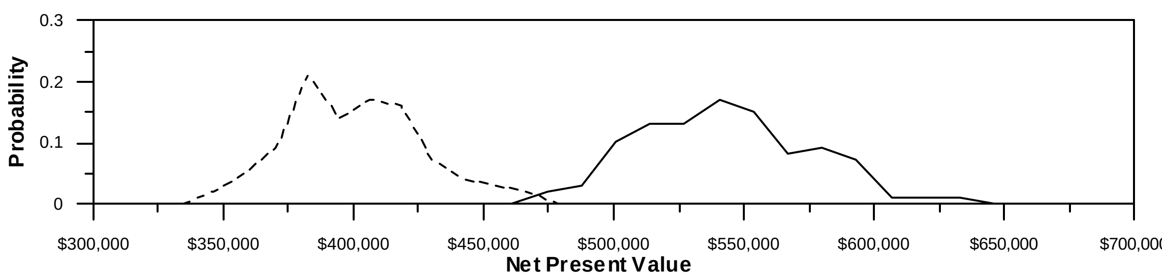
(a) Scenario 1, [concrete overlay; deck replacement]



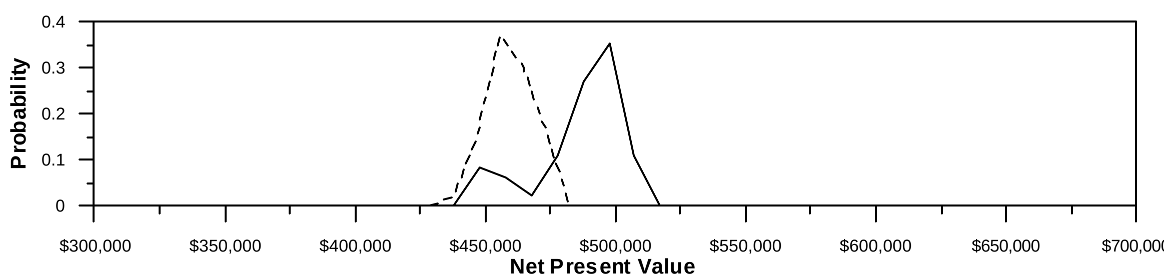
(b) Scenario 2, [patching; patching; patching; deck replacement]



(c) Scenario 3, [patching; patching; patching; AC overlay w/o membrane; deck replacement]



(d) Scenario 4, [AC overlay w/ membrane]



(e) Scenario 5, [Deck replacement]

Figure 17. Comparison of probability distribution of life-cycle costs using 3% and 4.5% discount rate (B-41-43, S_m=23)

CHAPTER 4. SPREADSHEET TOOL FOR PREDICTING SERVICE LIFE AND LCCA OF CONCRETE BRIDGE DECKS (USER MANUAL)

4.1 Capabilities of The Tool

BridgeDeck-LCCA.xls is a Microsoft® Excel worksheet application. It allows users to compute the performance curve of an existing bridge deck, to estimate the performance and service life of different repair strategies for the deck, and to conduct life-cycle cost analyses to compare the long term costs among different maintenance scenarios. The tool is based on the methodology and modifications described in Chapters 2 and 3.

4.2 Data Requirements and Assumptions

The following data are required as input for the computation of the performance curves, the service lives and the LCCA. It should be noted that different sets data are required for decks not repaired previously and for decks repaired previously. In the following, the chloride content data are expressed as a percentage of concrete weight.

4.2.1 Bridge Data

- Bridge identification number (ID)
- Year constructed (or reconstructed)
- Deck area
- Percent of delaminated area of concrete (not including spalls)
- Percent of spalled area of concrete
- Percent of concrete samples with bar-level chloride content higher than 0.035
- Year of survey: This is the year when the delaminated and spalled areas and chloride content were obtained.

Note 1: Currently, distressed data are collected every two years as part of the routine element inspection. Chloride content data are obtained only on a case-by-case basis. If delamination, spall, and chloride data are not collected at the same, the percentage of delaminated and spalled areas should be estimated at the time when the chloride content data was obtained.

Note 2: When the individual percentages of delaminated and spalled concrete areas are unknown, a 3:1 ratio of delaminated to spalled areas is recommended. For example, a bridge deck assigned a PONTIS condition state of 4 has a total distressed area (combined delaminations and spalls) between 10 and 25 percent. Assuming conservatively that the distressed area is 25%, 18.75% concrete area should then be considered as the delaminated concrete area, and 6.25% concrete area should be considered as the spalled concrete area.

<u>i) Bridge decks not repaired previously:</u>

- Average surface chloride concentration (from 0.25 to 0.75 inch deep)
- Standard deviation of surface chloride concentration as a percent of concrete weight
- Year when surface chloride concentration was measured
- Average depth of bar cover
- Standard deviation of bar cover
- Concrete water-cement ratio
- Average wet resistivity
- Snowfall range

Note: Some of the data, such as average wet resistivity and snowfall range, may be optional depending on the data entered in the 4.2.1 section. In the tool, the required data are shown in the highlighted cells.

<u>ii) Bridge decks repaired previously:</u>

- Year deck was last repaired
- Percent of concrete samples with bar-level chloride content higher than 0.035 immediately after treatment was done
- Average surface chloride concentration (from 0.25 to 0.75 inch deep)
- Standard deviation of surface chloride concentration, percent of concrete weight
- Year when surface chloride concentration was measured
- Average depth of bar cover
- Standard deviation of bar cover
- Concrete water-cement ratio

Note: If the percent of concrete samples with bar-level chloride content higher than 0.035 immediately after the treatment is not available, 50% of the concrete samples with chloride content higher than 0.035 may be assumed.

4.2.2 LCCA data

- Analysis period for life-cycle cost analysis (years)

- Life-cycle cost analysis base year (or current year):

  The life-cycle cost will be presented in terms of the present value at the base year.

- Discount rate (percent)

4.2.3 Treatment data

- Minimum, most likely, and maximum values for agency unit cost of treatments (dollars/ft^2)

- Minimum, most likely, and maximum values for the K factor of treatments (except for deck replacement)

- Minimum, most likely, and maximum value of the prefixed (offset) time of a new deck with epoxy coated reinforcement (years)

- Total time to conduct the treatment (days)

- Traffic control:

  Enter 1 if a detour will be scheduled or enter 2 if traffic will be allowed on the bridge while the treatment is performed.

4.2.4 User cost data

- Value of bridge user time while traveling, dollars per hour per vehicle

- Average two-way daily traffic volume across the bridge (ADT), vehicles per day

- Percent of ADT increase per year

- Free-flow travel time across the bridge, minutes

- Percent increase in free-flow travel time if the deck is in the worst tolerable condition

<u>i) For detour while treatment is performed:</u>

- Increment in travel time in detour around the bridge caused by construction, minutes

<u>ii) For traffic across the bridge while treatment is performed:</u>

- Two-way capacity of the bridge during normal periods, vehicles per day
- Two-way capacity of the bridge during construction, vehicles per day

4.3 Procedure of LCCA

There are eight steps to conduct a LCCA for selected maintenance scenarios. In step 1, the application is executed. In steps 2 to 3, the performance curve of the bridge deck is calculated. In step 4, the user selects the maximum tolerable condition index. Steps 5 to 8 runs the LCCA for selected maintenance scenarios.

Step 1: Execute BridgeDeck-LCCA.xls

Double click on BridgeDeck-LCCA.xls file. Make sure to **Enable Macros** upon running the tool.

Step 2: Input bridge data

Enter bridge data in sheet "(1) Input-Bridge Data". The required data must be entered in the highlighted cells.

Bridge decks not repaired previously: Click the **Not Repaired Previously** button. The data required for a bridge deck not repaired previously will then appear. The required data are shown in the highlighted cells.

Bridge decks repaired previously: Click the **Repaired Previously** button. The data required for a bridge deck repaired previously will then appear. The required data are shown in the highlighted cells.

Step 3: Compute performance curve

After entering the bridge data, click the **Compute Performance Curve** button in sheet "(1) Input-Bridge Data".

Bridge decks not repaired previously: Sheet "1b) Performance Curve (not repaired)" will show up. It shows the graph of the performance curve and its equation.

Bridge decks repaired previously: Sheet "1a) Performance Curve (repaired)" will appear. It shows the graph of the performance curve and its equation.

Click the **See Calculation** button to show the detailed calculation. Click the **Back to Performance Curve** button in the sheet with detailed calculation to close it and to go back to the sheet with the graph of the performance curve.

Step 4: Input maximum tolerable condition index

Bridge decks not repaired previously: Enter the value of the maximum tolerable condition index (S_m) in sheet "1b) Performance Curve (not repaired)". The year when the deck is expected to reach the maximum tolerable condition index is calculated and shown in a vertical line in the graph of the performance curve.

Bridge decks repaired previously: Enter the value of the maximum tolerable condition index (S_m) in sheet "1a) Performance Curve (repaired)". The year when the deck is expected to reach the maximum tolerable condition index is calculated and shown in a vertical line in the graph of the performance curve.

Step 5: Input LCCA data and select maintenance scenario

After entering the maximum tolerable condition index, click the **Input LCCA Data & Select Maintenance Scenario** button. Sheet "(2) Input-LCCA data & scenario" will be opened.

(i) Enter required data for LCCA as listed in section 4.2.

(ii) Enter the year to perform first treatment for the selected scenario.

For example, year 2002 is entered and scenario 1 is selected. Scenario 1 assumes a concrete overlay followed by deck replacement. This sequence is repeated during the service life of the deck. Therefore, the first treatment for scenario 1 (i.e., concrete overlay) will be performed in 2002.

(iii) Choose one maintenance scenario.

For each scenario, a semicolon delimits treatments and the series of treatments in brackets are assumed to be repeated until the end of the analysis period. Currently, there are five possible scenarios to select:

1. [Concrete overlay; deck replacement]
2. [Patching; patching; patching; deck replacement]
3. [Patching; patching; patching; AC overlay w/o membrane; deck replacement]
4. [AC overlay with membrane]
5. [Deck replacement]

Note: Scenario 5 is the base scenario used to compare with other scenarios. You must run scenario 5 first, and then run other scenario to compare with it.

Step 6: Input treatment cost and productivity data of the treatments

Click the **Enter Treatment Costs and Productivity** button in sheet "(2) Input-LCCA data & Scenario". Sheet "(3) Input-Treatment Costs" will be opened to allow users to enter treatment data. Cells with required data are highlighted.

Step 7: Input user costs data

Click the **Enter User Costs** button in sheet "(3) Input-Treatment Costs" to open sheet "(4) Input-User Costs" for entering user cost data.

Step 8: Run LCCA

Click the **Run LCCA** button in sheet "(4) Input-User Costs" to run life-cycle cost analysis.

Because scenario 5 is the based scenario, it should be selected to run the LCCA first, as mentioned in step 5. After running LCCA for scenario 5, sheet "Scenario 5" that contains all 100 Monte Carlo simulation results of LCCA for scenario 5 will show up in the horizontal scroll bar. At the same time, sheet "(2) Input – LCCA data & Scenario" will be opened to ask input of another scenario. Input another scenario and then repeat Step 6 to 8 to enter the data for the selected scenario and run the life-cycle cost analysis.

The sheet “Scenario 5” contained 100 Monte Carlo simulation results of LCCA includes estimated service life and unit agency cost of treatments, present values of agency cost, user cost during the treatment, and user cost prior the treatment, salvage value, total cost, average agency cost, and convergence.

For example, assume that scenario 1 is selected to do the comparison with scenario 5. Enter 1 in the sheet “(2) Input-LCCA data & Scenario” to select scenario 1 and then repeat Step 6 to 8 to enter the data for this scenario. After Step 8, clicking on the Run LCCA button, it will create a “Scenario 1” sheet in the horizontal scroll bar. At the same time, sheet “graphs (1&5)” will be opened. Sheet “graph (1&5)” contains a summary of LCCA results for scenarios 1 and 5, the graphs of histogram NPV, cumulative NPV, and the performance curves. After running LCCA for scenario 1, the user can run LCCA for other scenarios by clicking the sheet “(2) Input-LCCA data & Scenario” to enter another scenario and then repeat Step 6 to 8 as described above.

Note: Scenarios should be compared under same conditions, such as same maximum tolerable index, and the same timing to perform scenarios. If any condition is changed, LCCA for scenario 5 need to be run again, and then run the LCCA for other scenarios to do the comparison.

4.4 Example

This example illustrates how the BridgeDeck_LCCA.xls worksheet application works. This example will go though the procedure step by step. The bridge deck example is B-41-43.

Step 1: Execute BridgeDeck_LCCA.xls

After open the BridgeDeck_LCCA.xls and enable Macros, sheet “(1) Input-Bridge Data” shows up.

Step 2: Input bridge data

Enter bridge data required in the highlighted cells as shown in Figure 18. B-41-43 was built in 1963 with an area of 6082 ft^2. The chloride content inspection was taken in year 2000. The percent of concrete samples with bar-level chloride content higher than 0.035 percent of concrete weight is 100%. In the inspection report of the year 2000, a PONTIS condition rate of 4 was assigned to the deck, but the individual percentages of delaminated and spalled areas were not reported. In this example, it was assumed that 18.75% was delaminated and 6.25% was spalled, for a total distress area of 25% of the deck area.

	A–G	H	I
1	**(1) Bridge Deck Data Input**		
2			
3			
4	Date :	9/12/2001	
5			
6	Bridge ID	B-41-43	
7	Year (Re)Constructed (y0)	1963	
8	Deck area (A)	6082	ft^2
9	Year of survey (yp)	2000	
10	Percent of concrete area delaminated (DELAM)	18.75	%
11	Percent of concrete area spalled (SPALL)	6.25	%
12	Percent of concrete samples with bar-level chloride content higher than 0.035 percent of concrete weight (CL)	100	%
13			
14	Was concrete repaired previously? Not Repaired Previously		
15			
16	Repaired Previously		
17			
18	For concrete **REPAIRED** previously only		
19	Year Reparied (yr)	1978	
20	Precent of concrete samples with bar-level chloride content higher than 0.035 percent of concrete weight immediately after repaired (CLr)	50	%
21	Surface chloride concentration, percent of concrete weight (Zt)		
22	Average surface chloride concentration (AVzt)	0.16	%
23	Standard deviation (SDzt)	0.18	%
24	Year when surface chloride concentration was measured (yz)	2000	
25	Depth of bar cover (d)		
26	Average depth (AVd)	4	inches
27	Standard deviation (SDd)	0.5	inches
28	Concrete water-cement ratio (P)	0.48	
29			
30			
31	Compute Performance Curve		
32			
33			

(1)Input-Bridge Data

Figure 18. Sheet "(1) Input-Bridge Data" in BridgeDeck_LCCA.xls

A concrete overlay was performed in 1978 for this deck. Therefore, after entering the above data, click the **Repaired Previously** button to show other required data. The percent of concrete samples with bar-level chloride content higher than 0.035 percent of concrete weight immediately after repaired was not available. 50% of the samples were then assumed to exceed 0.035. From the chloride content report of year 2000 for this bridge deck, the average surface chloride concentration is 0.16% with a standard deviation of 0.18%. The average bar cover is 4 inches with a standard deviation of 0.5 inches. The concrete water-cement ratio is assumed to be 0.48.

Step 3: Compute performance curve

After entering all data in step 2, click the **Compute Performance Curve** button to see the performance curve of the deck. Figure 19 shows the corresponding sheet "1a) Performance Curve (repaired)".

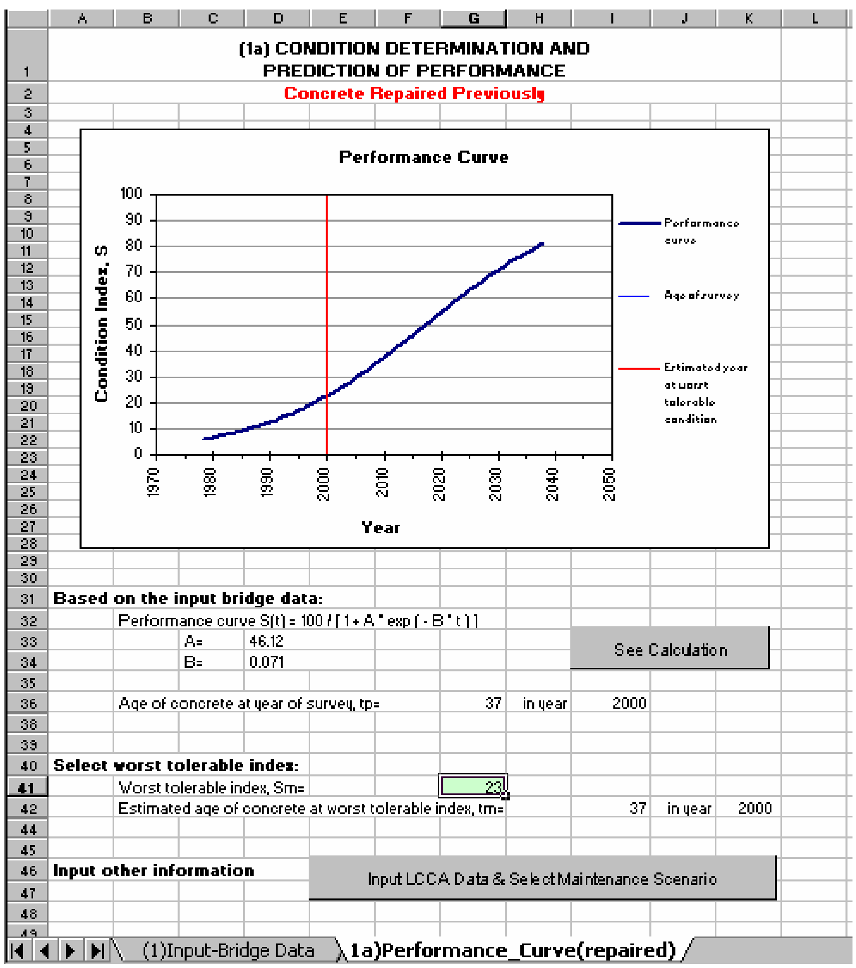


Figure 19. Sheet "1a) Performance Curve (repaired)" in BridgeDeck_LCCA.xls

Step 4: Input maximum tolerable condition index

The maximum tolerable condition index is assumed 23 in this example. Enter this value in the highlighted cell.

Step 5: Input LCCA data and select maintenance scenario

Click the **Input LCCA Data & Select Maintenance Scenario** button. Sheet "(2) Input-LCCA data & scenario" will be opened as in Figure 20.

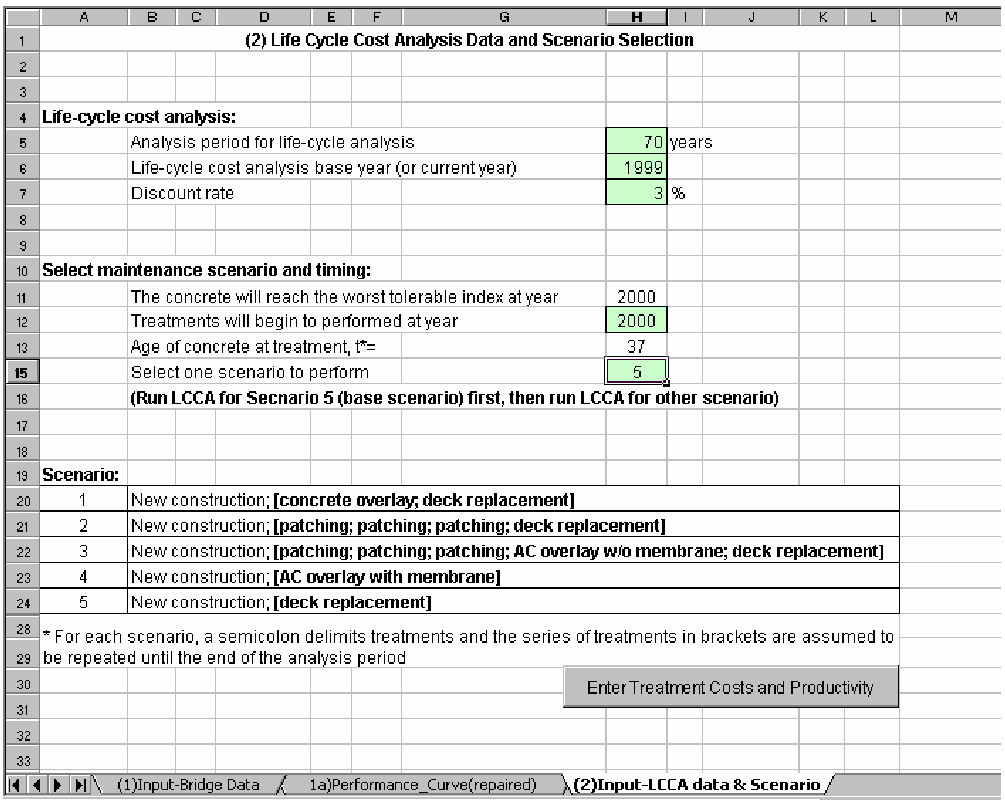


Figure 20. Sheet "(2) Input-LCCA data & scenario" in BridgeDeck_LCCA.xls

(i) Enter data for LCCA data. The analysis period for life-cycle cost analysis is assumed 70 years. The base year is selected as 1999 and a discount rate of 3% is assumed.

(ii) Enter data for maintenance scenario. The year to perform first treatment is selected as the year 2000. Scenario 5 is chosen first for the based case.

Step 6: Input treatment cost and productivity data of the treatment in the selected scenario

Click the **Enter Treatment Costs and Productivity** button. Sheet "(3) Input-Treatment Costs" will be opened as shown in Figure 21. Enter the required data with highlighted cells. In this example, WisDOT-recommended ranges of unit agency cost and offset value are used. The total time to conduct the treatment is assumed 45 days with detour (1) while construction.

(3) Treatment Costs and Productivity Input

		Recommended Value						Value used for analysis							
		Unit Agency Cost (dollars/ft²)			K*			Unit Agency Cost (dollars/ft²)			K*				Detour when construction? (1: Detour, 2: Traffic on bridge)
Items	Name of treatment	min	most likely	max	min	most likely	max	min	most likely	max	min	most likely	max	Productivity (days)	
1	Patching	10	15	20	0.9	0.95	1	10	15	20	0.9	0.95	1	5	1
2	Concrete overlay	25	30	35	0.05	0.125	0.2	25	30	35	0.05	0.125	0.2	20	1
3	AC overlay w/o membrance	4	5	6	0.9	0.95	1	4	5	6	0.9	0.95	1	10	1
4	AC overlay with membrance	5	7.5	10	0.65	0.7	0.75	5	7.5	10	0.65	0.7	0.75	10	1

		Cost (dollars/ft²)			Offset (years)			Cost (dollars/ft²)			Offset (years)				Detour when construction? (1: Detour, 2: Traffic on bridge)
Items	Name of treatment	min	most likely	max	min	most likely	max	min	most likely	max	min	most likely	max	Productivity (days)	
5	Deck replacement	35	37	40	25	30	35	35	37	40	25	30	35	45	1

* K is the ratio of the slope of corrosion rate increase after treatment to the slope of corrosion rate increase before treatment.
(1) K=1: The rate of corrosion continues to increase at the same rate after the treatment.
(2) 0<K<1: The rate of corrosion increases gradually after the treatment, but at a slower rate.
(3) K=0: The rate of corrosion levels off after the treatment.
(4) K<0: The rate of corrosion decreases gradually after the treatment.
(5) K=infinity: The rate of corrosion drops to 0 after the treatment.

Enter User Costs

(1)Input-Bridge Data / 1a)Performance_Curve(repaired) / (2)Input-LCCA data & Scenario / (3)Input-Treatment Costs

Figure 21. Sheet "(3) Input-Treatment Costs" in BridgeDeck_LCCA.xls

Step 7: Input user costs data

Click the **Enter User Costs** button. Sheet "(4) Input-User Costs" will be displayed as shown in Figure 22. The required user cost data are shown in highlighted cells.

(4) User Costs Data Input

Value of bridge user time while traveling (K1) (Travel time cost)	9.996	$/hr/vehicle
ADT two-way daily traffic volume across the bridge (qo)	15000	vehicles/day
Percent of ADT increases per year	1	%
Free-flow travel time across the bridge (tf)	0.06	minutes
Percent increase in free-flow travel time if deck is in the worst tolerable condition (a)	50	%
For Detour when constructionv Only		
Increment in travel time in detour around the bridge caused by construction (tt)	2	minute
For Traffic across the bridge when construction Only		
Two-way capacity of the bridge during normal periods (C)	15000	vehicle/day
Two-way capacity of the bridge during construction (C1)	5000	vehicle/day

Run LCCA

1a)Performance_Curve(repaired) / (2)Input-LCCA data & Scenario / (3)Input-Treatment Costs / (4)Input-User Costs

Figure 22. Sheet "(4) Input-User Costs" in BridgeDeck_LCCA.xls

Step 8: Run LCCA

Click the **Run LCCA** button. The application will conduct the LCCA and then go back to Sheet “(2) Input-LCCA data & Scenario” to ask for another scenario input for comparison. Scenario 1 is chosen this time to run the LCCA. Enter the number 1 to select scenario. The data in sheet “(2) Input-LCCA data & Scenario” will remain the same. Repeat Steps 6 to 8 to conduct the LCCA for scenario 1.

After conducting the LCCA for scenario 5 and scenario 1, sheet “graphs (1&5)” will be opened as in Figure 23. It summarizes the LCCA results for two scenarios (1 and 5) and present the histogram of NPV and cumulative probability of life-cycle costs for these two scenarios.

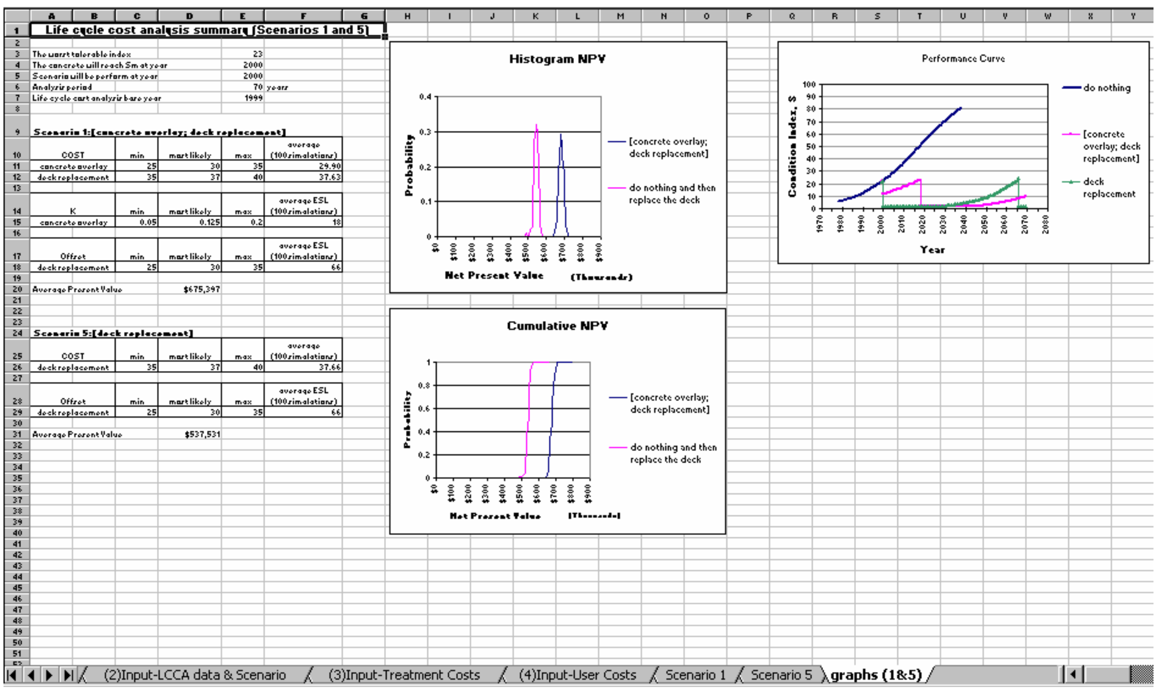


Figure 23. Sheet “graphs (1&5)” in BridgeDecl_LCCA.xls

For detailed Monte Carlo simulation results, select sheet “Scenario 1” for scenario 1 and sheet “Scenario 5” for scenario 5. To conduct the LCCA for another scenario, select sheet “(2) Input-LCCA data & Scenario” to select a different scenario and repeat steps 6 to 8.

CHAPTER 5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Bridge management requires a unique blend of structural engineering, economic analysis, operations research, planning and programming, and information technology. Particular challenges for current bridge management are the development and implementation of models for deterioration and life-cycle cost analysis, and evaluation of the effects of maintenance on the service life of the existing structures. Despite the recent development of bridge management systems, bridge managers continue to make decisions about maintenance strategies largely without life-cycle analysis tools. This is especially true for decisions made at the project level.

To bridge the gap between project and network level tools, a number of information issues must be addressed. First, a method is needed to match the condition rating scales used at the network level with those at the project level so that the worst tolerable condition is consistent across both systems. Second, the average estimated service life of maintenance actions should be equivalent at the network and project levels. Third, the least cost maintenance action at the network level should translate into alternative scenarios for life-cycle maintenance at the project level. Finally, element inspection data collected for network level analysis should feed into the project-level tools.

Initial research activities under this project involved a literature search and a survey questionnaire (sent to all eight districts in Wisconsin) to identify nondestructive testing methods for assessing the condition of concrete bridge elements. The methods were compiled and classified according to the type of distress identified by the method (cracking, delaminations, etc.) for typical concrete elements. Some NDT methods are currently being used by the Districts in Wisconsin, particularly for detecting delamination in bridge decks. Based upon these findings, the Project Committee recommended that the research plan focus on decision-making for treating corrosion and delamination of bridge decks.

This research describes a procedure for the life-cycle treatment of concrete bridge decks and extends the development of a project-level tool. The work focuses on developing the LCCA capability of the tool and on making the tool compatible with the currently available network-level bridge management systems. To this end, data from element level inspections were used to validate and calibrate the deterioration model. In addition, a set of life-cycle scenarios that are routinely used by state and local agencies was used to conduct a LCCA of an existing bridge in the state of Wisconsin. The project-level tool developed in this investigation allows bridge maintenance engineers to:

e) construct a performance curve for existing bridge decks, either repaired or not repaired previously,

f) compute the estimated service life of common treatments for bridge decks such as patching, concrete or asphaltic overlays as well as that of a new deck with epoxy coated bars.

g) conduct a life-cycle cost analysis for common maintenance scenarios.

h) determine the optimal maximum (tolerable) condition index that minimizes total life-cycle maintenance cost.

Findings and Conclusions

Based on the assumptions, data and life-cycle cost analyses of the maintenance scenarios considered in this study, the following findings and conclusions may be offered:

a) The choice of discount rate can significantly affect the total life-cycle cost of a given maintenance scenario. For the test case for AC overlay with membrane, the expected total life-cycle cost decreased by 26.5 percent when the discount rate increased from 3 to 4.5 percent. For the other scenarios, the reduction in the total cost ranged between 5.6 and 12.5 percent. Because the cash flows are non-uniform, the decrease is non-uniform across the maintenance scenarios. The decrease is especially noticeable for scenarios with costly treatment performed later in the life cycle.

b) The least cost maintenance scenario may depend on the choice of discount rate. For the test case, using a discount rate of 3 percent and maximum tolerable index S_m of 23, deck replacement with epoxy coated bars yielded the least life-cycle cost. For a discount rate of 4.5 percent, however, an AC overlay with membrane yielded the least life-cycle cost.

c) Total life-cycle cost is a function of the maximum tolerable condition S_m. The analyses showed that the minimum total life-cycle cost can be strongly influenced by the choice of the maximum tolerable condition index S_m. For example, the analyses showed that the total cost may vary by as much as 24 percent when S_m varied between 23 (value that represents current practice in Wisconsin) and 35 (maximum plausible value for practical purposes).

e) Furthermore, the relationship between total life-cycle cost and S_m is convex. This means that there is a particular value of S_m that minimizes the total life-cycle cost. The test case shows that the minimum total life-cycle cost is not necessarily achieved at the tolerable index currently used in Wisconsin (S_m =23). Depending on the maintenance scenario considered, a higher value of S_m may lead to a lower total life-cycle cost. The spreadsheet tool can be used to find the value of tolerable index that minimizes life-cycle cost.

5.3 Recommendations for Further Action

The research presented illustrates the integration of network and project level tools. However, element data collected for network analysis does not fully satisfy project-level analysis needs. In this regard, the Research Team offers five recommendations.

First, spalled and delaminated areas are recorded as a combined percentage of the distressed area in the current element-level inspection of concrete bridge decks. However, mechanistic deterioration models treat delamination and spalling as distinct phases in the deterioration process. The individual percentages of spalled and delaminated areas can have a significant influence on the calculated condition index of the deck. The findings in this research are based upon an assumed delaminated to spalled area ratio of 3:1. The Research Team recommends that the percentages of spalled and delaminated areas be collected and recorded as separate data items when bridges are inspected.

Second, Infrared Thermography (IRT) and Ground Penetration Radar (GPR) are two nondestructive methods being used to estimate the percentage of delaminated area in concrete decks. The Research Team is unaware of previous work to evaluate the consistency of results from these methods. Thus, it is recommended that a study be conducted to cross exam and corroborate results obtained from chain drag, IRT, and GPR.

Third, the chloride content is an essential parameter for modeling the deterioration and estimating the service life of existing bridge decks with and without treatment. Samples of the chloride content at the bar level are not collected in routine inspections and thus are unavailable for the majority of existing bridge decks. In order to further validate and improve upon the procedures presented here, data on chloride content data on a larger pool of bridge decks must be available. In lieu of a chloride content dataset or until one can be established, the Research Team recommends that WisDOT prepare a table of default values for chloride content as a function of concrete age, roadway functional class, and salt rate for winter maintenance.

Fourth, chloride extraction, corrosion inhibitors, and cathodic protection were identified as candidate maintenance treatments for concrete decks that can be included in the library of strategies known to the software application. The spreadsheet tool can be useful for evaluating the economics of these strategies as compared to more traditional strategies such as concrete overlay. The Research Team recommends that WisDOT collect the model parameters (cost, service life, productivity) necessary to include these strategies as possible maintenance scenarios.

Finally, the Research Team conducted a demonstration of the software application to members of the Project Committee. Suggested revisions from that meeting were incorporated into the program. The software is easy to use and this report includes a user manual in Chapter 4. Nevertheless, the Research Team recommends that WisDOT identify an "implementation champion" at Central Office to work with the Districts to further test and refine the software parameters and user interface so that the tool is integrated into the bridge management business function.

REFERENCES

(1) Small, E. P., and Cooper, J. Condition of the Nation's Highway Bridges – A Look at the Past, Present, and Future. *TR News*, Vol. 194, January-February 1998, pp. 3-8.

(2) Cady, P. D., and Weyer, R. E. Predicting Service Life of Concrete Bridge Decks Subject to Reinforcement Corrosion. *Corrosion Forms and Control for Infrastructure*, *ASTM STP*, Vol. 1137, 1992, pp. 328-338.

(3) Purvis, R. L., and Babaei, K. Selecting Bridge Protection and Rehabilitation Options. *Proceedings of Pacific Rim*, *TransTech Conference*, Seattle, Washington, 1993, pp. 357-368.

(4) Babaei, K., Purvis, R. L., Clear, K. C., and Weyer, R. E. Methodology for Concrete Removal, Protection, and Rehabilitation. Prepared for the U.S. Department of Transportation, Federal Highway Administration, Wilbur Smith Associates, June 1996.

(5) Life-Cycle Cost Analysis in Pavement Design. FHWA-SA-98-079, U.S Department of Transportation, Federal Highway Administration, 1998.

(6) Freyermuth, C. L. Life-cycle cost analysis for large segmental bridges. *Concrete International*, Feb. 2001, pp. 89-95.

(7) Ehlen, M. A. Life-Cycle Costs of Fiber-Reinforced-Polymer Bridge Decks. *Journal of Materials in Civil Engineering*, Vol. 11, No. 3, 1999, pp. 224-230.

(8) Frangopol, D. M., Kong, J. S., and Gharaibeh, E. S. Reliability-Based Life-Cycle Management of Highway Bridges. *Journal of Computing in Civil Engineering*, Vol. 15, No. 1, 2001, pp. 27-34.

(9) Velivasakis, E. E., Henriksen, S. K., and Whitmore, D. W. Halting Corrosion by Chloride Extraction and Realkalization. *Concrete International*, Vol. 19, No. 12, 1997, pp. 39-45.

(10) Bennett, J. E. Stop Corrosion of Reinforced Concrete Structure. *Chemical Engineering Progress*, Vol. 94, No. 7, 1998, pp. 77-81.

(11) Whitmore, D., Abbott, S., and Velivasakis, E. Battling Concrete Corrosion. *Civil Engineering*, Vol. 69, No. 1, 1999, pp. 46-48.

(12) Gu, P., Elliott, S., Hristova, R., Beaudoin, J. J., Brousseau, R., and Baldock B. A Study of Corrosion Inhibitor Performance in Chloride Contaminated Concrete by Electrochemical Impenance Spectroscopy. *ACI Material Journal*, Vol. 94, No. 5, 1997, pp. 385-395.

(13) Bjegovic, D., and Miksic, B. Migrating Corrosion Inhibitors Protection of Concrete. *Materials Performance*, Vol. 38, No. 11, 1999, pp. 52-56.

(14) Sprinkel, M., and Ozyildirim, C. Field Evaluation of Corrosion Inhitibors for Concrete: Interim Report 1: Evaluation of Exposure Slabs Repaired With Corrosion Inhibitors. Virginia Transportation Research, 1998.

(15) Sprinkel, M., and Ozyildirim, C. Field Evaluation of Corrosion Inhitibors for Concrete: Interim Report 2: Evaluation of Installation and Initial Condition of Bridge Repairs Done with Corrosion-Inhibiting Admistures and Topical Treatment. Virginia Transportation Research, 1999.

(16) Polder, R. B. Cathodic Protection of Reinforced Concrete Structures in the Netherlands – experience and developments. *Heron*, Vol. 43, No. 1, 1998, pp. 3-14.

(17) Abby McKenzie. Economic Analysis and Special Studies, Mn/DOT Office of Investment Management, www.oim.dot.state.mn.us/EASS/, 2001.

APPENDIX A. BRIDGE DECK SAMPLES

The two bridges selected are B-41-43 in District 5 and B-35-10 in District 7. These bridges were chosen because field test results of the chloride content of the decks (a necessary input data item of the methodology) were available. The chloride tests were performed in the 2000 and 1999, respectively. Detailed inspection reports for these two bridges were obtained from District 5 and the Central Office.

BRIDGE B-35-10

Bridge B-35-10, located at Lincoln County, District 7, WI, was built at 1922, and was widened the structure at 1960. The structure length is 455.1 ft and the curb-to-curb width is 44 ft. It's a six span bridge with 24,574 ft^2 deck areas. A concrete overlay was performed at 1979. From the inspection report, another concrete overlay was recommended to perform in 1997. The inspection data was recoded from 1990, but was integrated into PONTIS system from 1997. The condition of bridge deck reported in the inspection report is summarized in Table A.

Table A. Summary of condition rating of B-35-10 deck

Years	Inspection Items	NBI Rating	PONTIS C.S.I	Comments
1990	Floor material concrete (1960)	6		Delaminated 20% sounding.
	Wearing surface concrete (1979)	5		
1991	Floor material concrete (1960)	6		Delaminated 20% sounding.
	Wearing surface concrete (1979)	5		
1992	Floor material concrete (1960)	6		Delaminated 20% sounding.
	Wearing surface concrete (1979)	5		
1993	Floor material concrete (1960)	6		
	Wearing surface concrete (1979)	6		
1994	Floor material concrete (1960)	6		Delaminated 59% sounding.
	Wearing surface concrete (1979)	4		
1995	Floor material concrete (1960)	6		Delaminated 59% sounding. Delaminated 12.1% infrared.
	Wearing surface concrete (1979)	4		
1997	Concrete deck protection		4	Delaminated 19.2% sounding.
1998	Concrete deck protection		4	
1999	Concrete deck protection		4	Delaminated 26.4% sounding. Chloride testing conducted.

BRIDGE B-35-10

Bridge B-41-43, located at Monroe County, District 5, WI, was built at 1963. The structure length is 135.2 ft and the curb-to-curb width is 40 ft. It's a three span bridge with 6,082 ft^2 deck areas. A concrete overlay was performed at 1978. From the 2000 inspection report, another concrete overlay is scheduled in 2004. The condition of bridge deck is summarized in Table B.

Table B. Summary of condition rating of B-41-43 deck

Years	Bridge element	PONTIS C.S.I	Comments
2000	Concrete slab protected with rigid overlay	4	Delaminated 10% in 1995

This deck was given a PONTIS element condition state rating of 4 in the 2000 inspection report, which represents a distressed area (spalled or delaminate) between 10 and 25 percent of the total deck area. The specific percentages of spalled or delaminated areas were not available. In this study, 25 percent was selected as a conservative estimate of the combined spalled and delaminated areas. WisDOT recommends a 1:3 ratio of spalled to delaminated areas, thus for analysis purpose, the deck area is assigned to be with 6.25 percent spalled and 18.75 percent of delaminated.

IMPLEMENTATION PLAN

WisDOT Research

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Implementation of Research Results

Project Information	
Project Title: Assessment and Rehabilitation Strategies / Guidelines to Maximize the Service Life of Concrete Structures	**Project ID:** 0092-00-17 **Today's Date:** November 26, 2001
Technical Oversight Committee (WHRP or COR): WHRP Structures TOC	**TOC Chair and Phone number:** Stanley W. Woods (608) 266-8348
Project Start Date: October 1, 1999	**Approved Contract Amount:** $50,000
Project End Date: December 31, 2001	**Final Project Expenditures:** $50,000
Reference Final Report Draft Dated: November 30, 2001	
Principal Investigator: Teresa M. Adams, Ph.D. Professor, Civil and Environmental Engineering **Organization:** University of Wisconsin-Madison	**Phone:** (608) 262-5318 **E-Mail:** adams@engr.wisc.edu

Technical Oversight Committee Recommendations	
1. Check one of the two choices below: ☒ **Yes. We recommend changes to current practice based on some or all of the results of this report. The research was sound, and the report's conclusions appear to offer an advance over current practice.** ☐ **No. We do not recommend changes to current practice at this time. This approach does not appear fruitful OR future study is needed OR our objectives have changed, etc.**	
2. If implementation is not recommended, we suggest the following actions instead:	
3. If implementation is recommended, we suggest the following specific changes to current practice, detailed on the attached work plan and timeline (check applicable items): ☐ **Standard Specifications** ☐ **Quality Management Program (QMP) Specifications** ☐ **Facilities Development Manual (FDM)** ☐ **Highway Maintenance Manual** ☐ **Training, outreach** ☒ **Other (describe):** Element-level Inspection Reports and Bridge Inspectors Pocket Manual. For concrete deck elements, add data fields for % area spalled, % area delaminated, and chloride content if these data are collected.	
4. Approval of this implementation plan by the Technical Oversight Committee (chair on behalf of entire committee): WHRP Structures TOC Stanley W. Woods, Chair	**Signature:** **Date:**
5. Approval of this implementation plan by the Council on Research (for COR approved projects):	**Signature(s):** **Date:**
6. Referral for development of detailed work plan and timeline to (check one):	☐ **WisDOT/Industry Technical Committee on:** ________ ☐ **Other WisDOT policy body:** ________

7. Approval of work plan and timeline by the WisDOT Bureau Director(s) responsible for the policies described in item #3 above:	**Signature(s):** **Date**
8. Acceptance by a project manager of the responsibility for completing these implementation efforts according to the attached work plan and timeline:	**Signature:** **Date:**

Rev. 4/8/01

Implementation Work Plan	
1. Project Title: Implement Results of WHRP project 0092-00-17	**2. Prepared by:** Teresa M. Adams, Ph.D. and Stanley W. Woods, P.E.

1. Scope and objectives of implementation, including specific changes to WisDOT procedures.

Tasks:

1. Work with central office engineers to improve the user interface for the spreadsheet application.
2. Modify spreadsheet application to include a user interface for predicting future condition index (without running the LCCA) if certain actions are done.
3. Prepare table of default values for chloride content as a function of concrete age, roadway functional class, and salt rate for winter maintenance.
4. Determine models for maintenance cost as a function of concrete condition index (S).
5. Work with district engineers to test and refine the spreadsheet application.
6. Determine K factor, maintenance costs, and build LCCA models for chloride extraction, corrosion inhibitors, and cathodic protection.
7. Modify element-level inspection reports and Bridge Inspectors Pocket Manual to store additional optional data for concrete deck elements: % area spalled, % area delaminated, and chloride content. (This task could be deferred to a future WHRP project.)

2. Estimated cost (if any) to implement.

4. Expected benefits and how they will be measured (dollar savings, time savings, other).

WHRP Project 0092-00-17 result is a life-cycle cost analysis tool for selecting minimum cost maintenance strategies for concrete bridge deck projects. Implementation of project results is expected to yield agency and customer cost savings for life-cycle maintenance of concrete bridge decks. Exact costs savings are difficult to measure.

5. Possible pitfalls and how they will be avoided.

None identified

Implementation Timeline (Gantt Chart)

Tasks/Person Responsible\ Project Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1. Improve User Interface	xx	xx										
2. Predict Future Condition Index		xx										
3. Default Values of Chloride Content			xx	xx	xx							
4. Maintenance Cost Functions						xx	xx	xx				
5. Test and Refine at the Districts						xx	xx	xx				
6. Build Models for Chloride Extraction, Corrosion Inhibitors, and Cathodic Protection.									xx	xx	xx	xx
7. Modify Element-level Inspection Reports and Bridge Inspectors Pocket Manual			xx	xx	xx							

Rev. 5/8/01